KOSCIUSZKO ICE-AGE HERITAGE

Abstract

This document investigates the rationale behind the science of Geology and applies it to unravelling the character and genesis of the Kosciuszko Landscape during the Pleistocene Ice-Age.

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FORWARD

This book includes evidence from prior researchers of the Kosciuszko Landscape which has been checked in the field by this writer and supplemented with additional evidence located during the past 40 years.

It was relatively easy to retrace the steps of T W Edgeworth David at Kosciuszko in 1901, as he made detailed and accurate observations including chain and compass measurements to determine position and he presented maps and sections that were easy to comprehend.

Other researchers in the 20th century did not make such accurate observations of location or present their work with satisfactory maps. The availability today of accurate, hand held GPS (global positioning systems) and a network of satellites accessible by the civilian population has allowed accurate positioning of observations on grids such as the WGS84 (World Geodetic System, 1984), which is equivalent to the Australian GDA94, (Geocentric Datum of Australia, 1994). The GDA94 is used in the current 8525 series of 1:25 000 topographic maps at Kosciuszko first published in 2001 by the NSW Department of Lands from 1999 aerial photography.

In addition to topographic maps, improvements in satellite image resolution available via Google Earth make this an invaluable tool for earth scientists and although the images presented are not orthographic with a constant scale factor, they give useful insights into the landscape.

This book is not a systematic academic review of past research into the Kosciuszko Landscape. It is a search for valid evidence and the development of a model consistent with that evidence and I have attempted to acknowledge all prior discoveries.

In order to appreciate valid evidence, the reader needs some background into the principles of geology. The principles applied by earth scientists today were developed by Hutton, Smith, Charpentier, Agassiz and Lyell during the past 200 years. We will need to examine sediments and the larger particles within those sediments, with the naked eye as well as the broader landscape to include some context for the material being examined. Most readers will not be aware of the range of airborne geophysical tools that can be deployed by geological investigations today, but I am not relying on these tools because the evidence we will be examining needs to be found by searching for small exposures of rocky debris in a vegetated, alpine landscape.

This is how pioneers like James Hutton, William Smith, Horace Benedict de Saussure, Jean de Charpentier, Louis Agassiz and Charles Lyell operated and built the foundations of geology. Evidence can only be assessed and interpreted with the aid of basic, operational principles. The people mentioned above have developed, documented and utilised these principles which are based on an appreciation of natural processes. *The present is the key to the past*. These principles are applied to the case-study of the cliff exposure at Siccar Point, Scotland, in Chapter One and are the basis of modern stratigraphy. All the predictions and hypotheses made by Hutton during the late 18th Century concerning the transformation of sediment into hard crystalline rock have been verified in the 20th century and his proposition that a prior, widespread glaciation covered most of Europe in the recent past, which he

made 220 years ago, has been proved correct. Hutton was very aware that climate change moulded the outputs of the rock cycle.

My message here is that non specialists should not be afraid to look at geological evidence nor to make your own deductions. Chapters 1 to 6 are a journey through the development of rational observation in earth science against a background of ignorance and religious dogma. Let the work of an almost unknown Victorian dairy farmer, Charles Clifton Brittlebank, be an inspiration to you. He contradicted the geological establishment in 1894 (see chapter 5) and his observations and deductions were proved correct and they currently support the Plate Tectonic Model of the Earth, which developed during the late 20th Century.

The visual nature of the evidence that I will be discussing lends itself to photography, and to aid your appreciation of the character of glacial landscapes and the appearance of glacially abraded debris, I have included many photographs. To supplement this process, I have produced a Kosciuszko Photoglossary which attempts to illustrate and explain the features and processes relevant to this investigation which are usually taken for granted in specialised scientific publications. The early work into examining evidence at Kosciuszko by T. W. Edgeworth David was supplemented with photographs by pioneering Australian photographers: Judge Docker, E F Pitman and T W E David himself.

You will notice in the early chapters that the enlightened thinking of Hutton, Lyell and Agassiz received a very hostile reception from the intellectual establishment in 1840-1842. It is unfortunate that the conservative establishment of the 19th century relied on dogma rather than intellect and systematic observation.

We of the 21st Century do not have another hundred years to rescind ongoing conservative dogma that is in denial of reality, and is blocking intelligent solutions to the problems that beset life on this planet. Without the rapid implementation of solutions to these problems we could all be extinguished with very little trace in the ongoing geological record.

Read on and keep an open mind.

Edward Minty 14 11 2022.

Dedication and Acknowledgements

This book is dedicated to all those that will read it, and especially to those that will ***go and see***.

I am indebted to several people who have assisted me with fieldwork over many years, including my wife Glenda and my friends Don Mudge, Martin Fussell and Allan Curtis. Peter Pridmore gave me valuable feedback on the first draft of this document. I am also grateful to David Branagan for many years of encouragement and mentoring as well as access to original research papers and maps by T W Edgeworth David.

The contents of this book are my own work except for those references included in the text from other writers which are listed and commented on in the endnotes for each chapter, as guided by the Turabian referencing method.

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CHAPTER ONE: Dogma and Dedication or Three men in a Boat

This chapter outlines the philosophical turmoil surrounding James Hutton's ***Theory of the Earth*** (1795) and briefly describes a turning point in the acceptance of this geological model put forward by Hutton which involved a brief boat journey down the coast of Scotland.

Glaciation as a process of continental scale erosion has had a long and bumpy road as a scientific model. Scholars of the 17th Century attempted to interpret the natural world in relation to the Christian Old Testament, usually invoking a catastrophic flood or deposition from a primeval global ocean, to account for the development of rock-strata.

Researchers in the 17th Century had a different concept of time to that which we are familiar with today. Archbishop James Ussher (1581-1656) used the bible and other historical references to write *Annales veteris testament, a prima mundi origine deducti* in 1650, with a follow up article *Annalium pars posterior*, in 1654. In these he calculated the creation of Earth to have been at nightfall on 22nd October 4004BC. Other post reformist scholars, including Sir Isaac Newton also attempted this task.

In contrast, James Hutton (1726-1797), a Scottish farmer, industrial-chemist and geologist, made carefully reasoned arguments regarding observations of exposed rock strata. In 1788, Hutton presented his *Theory of the Earth* to the Royal Society of Edinburgh, where he explained his model of the "Rock Cycle". He argued that erosion of the Earth's crust and the transport and deposition of debris, generated new strata, or layers of rock, which are subsequently uplifted, tilted and then eroded away. Hutton concluded with: "**we find no vestige of a beginning, no prospect of an end.**"[1] This statement underpins Hutton's concept of *time* and the nature of the *rock cycle*.

Hutton theorised that changes in the disposition and texture of sediments, were driven by heat and pressure from deep within the earth. In June 1788, James Hutton and two colleagues: John Playfair (Professor of Mathematics at Edinburgh) and Sir James Hall, set off in a boat from Dunglass, Burn Beach, Scotland; sailing southwards along the coast in search of evidence.

James Hall, a Fellow of the Royal Society of Edinburgh, was at first sceptical of Hutton's *Theory of the Earth*. He provided the boat and crew for the search for evidence, which Hutton suggested could be found in the rock formations along the coast. Hutton was aware that two different formations of sedimentary rocks outcropped along this stretch of coast. When the group landed at Siccar Point, Hutton noted the unconformity, (or boundary), between the two formations exposed on the headland, and his colleagues were confronted with irrefutable proof of the immense span of time needed, to work through the processes evident in the rock exposure at Siccar Point.[2]

A sketch from a photograph of Siccar Point has been prepared by this author as figure 1.1, as a case study of the principles of stratigraphy, and it shows the two separate rock formations. The lower layer was originally laid out as horizontal beds of grey sediment but it has been subjected to heat and pressure which have compressed, hardened, folded and uplifted this formation; which has then been subjected to erosion at the earth's surface. This lower layer is now a *metamorphic* rock or *metasediment* due to these *changes*.

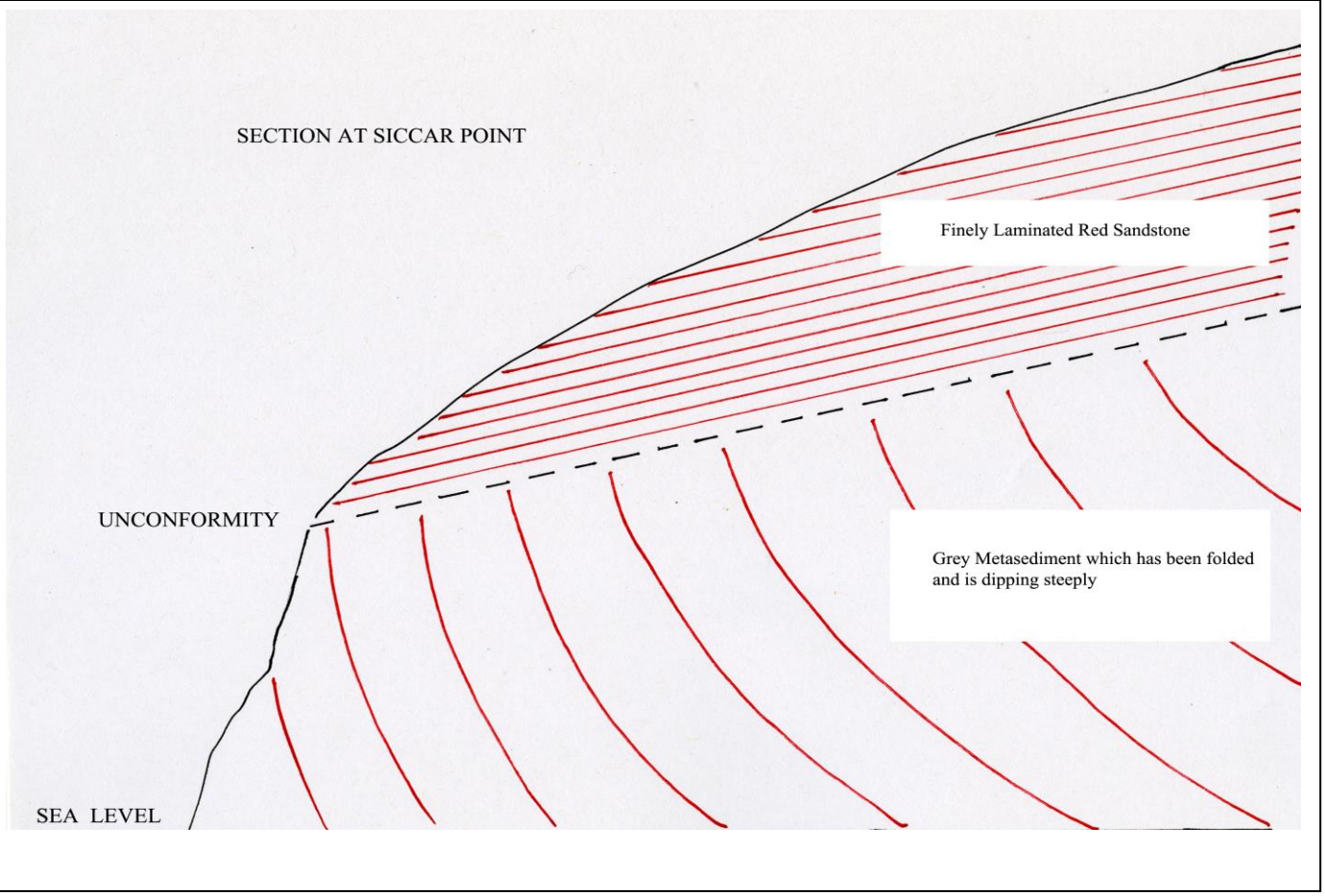

SECTION AT SICCAR POINT
Finely Laminated Red Sandstone
UNCONFORMITY
Grey Metasediment which has been folded and is dipping steeply
SEA LEVEL

Figure 1: **Cross- Section through Siccar Point**

The dashed line is the *unconformity* or break in time between the formation of the grey metasediment and the subsequent deposition of the overlying red laminated sandstone. The *unconformity is also an erosional-surface* and would have been roughly horizontal when active and just prior to the deposition of the red sandy layers. The force of gravity also makes most depositional surfaces close to horizontal, like the sand flats of a modern estuary. The laminations of red sand would have been near horizontal when deposited on top of the old erosion surface or unconformity.

Sediments generally settle out and form an equipotential surface during deposition from a fluid medium such as water, due to the influence of gravity. Since the deposition of the red sand, this sediment has been lithified or hardened into stone by the weight force of overlying material and also by the slow cementation of the sand particles, possibly by the precipitation of dissolved substances like iron oxides, which may have also given these sandy layers their red color. These two formations were not left in peace for long as the near horizontal and parallel laminations of the red sandstone have been tilted from their original position and the whole landscape has been uplifted again, causing erosion to reactivate and create a second unconformity or erosion-surface, which is the present upper surface we see today.

Back in 1788, Hutton and his colleagues did not have the tools of *radiometric dating* which we currently use to establish precise geological timing of events. However, they could observe some of these processes of erosion and sedimentary deposition actively working in their local landscape, and they realised the enormity of time needed to achieve the multiple processes evident in the section at Siccar Point. This modern appreciation of time was an enormous intellectual leap.

Although Hutton's *Theory of the Earth* was howled down by the establishment in Britain and France, his close colleagues appreciated his genius and his subsequent publications in 1795,[3] presented detailed arguments to face down that criticism. Much of the criticism was based on a literal belief in the book of genesis from the Christian Old Testament which constricted the conservative mindset in the comprehension of the concept of geological time. Hutton's publications were suppressed and may have been lost forever, if not for the ongoing promotion of Hutton's work by John Playfair, James Hall and later on, Charles Lyell.

James Hall carried out numerous experiments fusing and slowly recrystallising limestone and other mineral matter under high pressure and temperature to validate some of Hutton's assertions concerning the role of heat and pressure in the rock cycle. He also took a young Charles Lyell in 1824 to Siccar Point to examine Hutton's unconformity and discussed its relevance to the Rock Cycle with Lyell.[4]

Hutton's recognition of the *uniformity of processes past and present* is the guiding principle used by all field geologists up to the present time. The ongoing message here is that if you wish to understand the story implied by rock strata, or stratigraphy, you must go out into the field and observe natural processes in action as well as sections through the rock strata in order to interpret their relationships and origins. Hutton was a dedicated observer and one of his quotes after a long day in the saddle still rings true today: "**Lord, pity the poor arse clagged to a head that will hunt stones**", written in a letter to George Clerk Maxwell in the summer of 1774.[5]

John Playfair's 1802 *Illustrations of the Huttonian Theory of the Earth,* is commonly regarded as the earliest work to state that the European Alps had undergone an **extensive prior glaciation** and that glaciers had been responsible for transporting erratics into the Jura Mountains from Mont Blanc. However, this paper promoting Hutton's work was not the first to postulate past large scale glaciation.

In *Theory of the Earth* (1795), James Hutton referred to observations by H. B. de Saussure regarding blocks of granite, which had been transported from their original site on Mont Blanc across a broad valley and deposited on the limestone flanks of the Jura mountains. This deposit is over 100km from the granite's source and up to 1000m above the surrounding lowland terrain. These ***blocs de granit*** described by de Saussure and also by Hassenfratz, (1791) were reported in Hutton's *Theory of the Earth*.[6] Hutton then *speculated* on these observations of erratics in the Jura Mountains: *"...**We have but to enlarge our thoughts with regard to things past by attending to what we see at present...and we will understand .....those great blocks of granite so foreign to the place on which they [now] stand. [If we] now consider the height of the Alps ....to have been much greater than it is at present [then] there would have been immense valleys of ice sliding down in all directions towards the lower country,***

and carrying large blocks of granite to a great distance….such are the great blocks of granite which now repose upon the hills of Saleve".[7] This is the first English language text to speculate on a past extensive glaciation of Europe and is a beautiful example of the Principle of Uniformity.
Hutton probably relied on the published observations by de Saussure regarding active glaciers in the Swiss Alps, then applied his model of the rock-cycle to work back in time to visualise a prior ice-cap over the entire Swiss Alps, which subsequently explained *blocs de granit* on the Jura Mountains. There is no evidence that Hutton ever visited or explored the Swiss Alps.

Possibly the first description published in English of the granite erratics on the Jura mountains was by James David Forbes, in his 1843 book: *Travels through the Alps of Savoy and other parts of the Pennine Chain with observations of the phenomena of glaciers.*[8] Forbes travelled with Jean de Charpentier who had already described these granite blocks as ***blocs erratiques de la Suisse*** in his 1835 report: *Extrait du tome viii, des Annales des Mines*, and is therefore credited with the term **"erratic".**

Chapter Two A European Ice-Age

This chapter briefly describes the early development of our comprehension of glacial landscapes by Swiss researchers including: de Saussure, de Charpentier and Agassiz; and the attempts by Hutton and Buckland to convince the English of the existence of a prior, widespread Ice-Age over Europe and the United Kingdom.

The concept of a European Ice-Age during the recent past was an apparent contradiction of Genesis according to most scholars during the 18th and early 19th centuries. The English intellectual establishment in particular used Genesis to explain the formation of all unconsolidated sediment by means of a global flood or deluge. This was the basis of the *Diluvial Model* at that time.

Glacial erratics however, were well understood prior to the 19th century, only by the Swiss who lived on the margins of active glacial valleys, as subsequently reported by both of the French speaking Swiss researchers: Jean de Charpentier in *Extrait des tombe viii, des annales des Mines, 1835* and Louis Agassiz, in *Etudes sur les glaciers*, 1840. These ***erratics*** are pieces of rock carried by a glacier which appear out of place when compared to the underlying bedrock at their final resting place.

James Hutton discussed a very curious observation by de Saussure, who was the first to identify blocks of granite [erratics] sitting on the limestone flanks of the Jura mountains 100 km from their source at Mont Blanc. Hutton wrote: "*It is the finding the travelled materials of Mont Blanc, or fragments detached from the summit and centre of the Alps, in such places as give reason to conclude that they had passed through certain openings between the mountains of the Jura. This is a thing which he* [de Saussure] *thinks could not happen according to the ordinary course of nature*".[9]

The following two paragraphs describe the derivation of key concepts in the recognition of glacial landscapes. In addition to **glacial erratics**, the features we refer to as **roches moutonnées** and **moraines** are unique to glacial erosion and deposition.

Horace Benedict de Saussure, a gifted scientist, instrument maker and alpinist was the forerunner of quantitative research into the alpine terrain of the Swiss Alps, but despite his work "*in natural history* [being] *the most exemplary of its kind*",[10] some of his conclusions, were clouded by the dogmatic diluvial mindset.[11] De Saussure writes: (translated) "*Further on, behind the village of Juviana or environs, we see rock that has a shape that I call moutonnée. This unique landscape made up of vegetated bedrock is similar to a mature fleece or of those wigs which are also called moutonnée"*.[12] This metaphoric description of what has subsequently become a characteristic form of glacial abrasion (roche moutonnée) has created controversy to the present day.

Agassiz used the term ***roche polies*** (polished rock) instead of *roche moutonnée* to describe glacially sculpted bedrock and he also carefully qualified de Saussure's contribution by stating (translated): "*When a glacier encounters protruding bedrock on her path, she removes its edges, rounds it, and determines these bumpy shapes that de Saussure has called roches moutonnées*".[13] However, I cannot find any reference to *roches moutonnées* in any of de Saussure's work. He simply used the word "moutonnée" to describe the characteristic shape of certain unique hills or "montagnes" he had observed in the Alps. De Saussure does not appear to have associated glacial abrasion with the

formation of these moutonnées, unlike Louis Agassiz. Louis Agassiz also illustrated *roches moutonnées* in his accompanying *Atlas of Illustrations*: Plate 8; *Roches polies du glacier Zermatt*, which is discussed further in the *Kosciuszko Photoglossary*.
Moraines (the debris deposited as ridges near the snout or muzzle of glaciers) is a term attributed to de Saussure by Louis Agassiz. Louis wrote (translated): "*De Saussure is the first*[researcher] *who has carefully followed the moraines and who is concerned with their formation, their arrangement and the shape of the rocks which comprise them*".[14]

Conservative British geologists during the early 19th century were convinced that all recent looking sediments were deposited by a catastrophic flood as indicated in the book of Genesis from the Christian Old Testament. They shunned radical propositions regarding possible extensive continental glaciation in the past. The Geological Society of London, founded in 1807, accepted that an immense time had been needed to build up the huge thickness of rock strata visible in quarries and cliffs, but relied on religious dogma associated with Noah's flood, to explain unconsolidated strata of the uppermost layers.

Researchers at this time recognised that strata could be identified and characterised by the fossils they contained. From 1794 the canal engineer William Smith, mapped rocks and fossiliferous strata in England, Wales and parts of Scotland.[15] William Smith recognised that the sequence of sedimentary layers he was digging through were accompanied by a parallel sequence of fossils and that some of these fossils were unique to certain layers, and therefore these fossils were like a time-stamp which could be used to correlate rock layers occurring elsewhere in England.[16] On the 1st of August, 1815, with financial assistance from Joseph Banks,[17] Smith published the first Geological Map of Great Britain which remains the basis of all subsequent geological maps, with sedimentary layers arranged in relative order of age in the maps legend, as determined by their fossil content or age.

George Bellas Greenough, first president of the Geological Society of London, published a set of essays in 1819 titled: *A Critical Examination of the First Principles of Geology*. In this he attempted to refute Hutton's *Theory of the Earth* and he postulated a global **debacle** or **deluge** to account for the widespread occurrence of erratics in Europe and elsewhere.[18] However, Greenough was afflicted with a failure to comprehend geological time and geological processes of erosion, as well as recent advances in the correlation between strata as pioneered by William Smith.[19] Despite his dissembling criticism of Smiths contributions to geology, Greenough saw fit to plagiarise Smith's field notes and mapwork to produce his own version of the *Geological Map of England, Wales and Scotland*.[20]

The reverend William Buckland (1784-1856), became the foremost proponent of *Flood* or *Diluvial Geology*. He sought to get the new science of Geology accepted onto the curriculum of Oxford University. As the first professor of Geology at Oxford, his inaugural speech of 1819 *Vindiciae Geologicae* defended Geology against allegations that it undermined religion. Buckland considered that features like *erratic boulders*, extensive areas of gravel (*moraines*), and landforms which appeared to have been scoured by water, were unintelligible without recourse to a *deluge* exerting its ravages at a period not more ancient than that announced in the Book of Genesis.

Ironically, Buckland would later become a champion of Louis Agassiz's theory of past *continental glaciation* as a model to explain the *erratic blocks*, *moraines* and the sculpted landforms (*roches moutonnées* or *roche polies*), found over much of Europe and The United Kingdom.
In 1837, Louis Agassiz presented his *Discours de Neuchatel* address to the Societe Helvetique des Sciences Naturelles, describing a recent, major Ice Age in Europe. However, Agassiz was working for British patrons (including the Geological Society of London) as an expert vertebrate palaeontologist and his views on *continental glaciation* disturbed his British patrons. Buckland visited Agassiz in the summer of 1838 and pleaded with him to recant his outspoken view on widespread continental glaciation over much of Europe. It appears that Buckland's worth as a scholar conquered his religious prejudices, for after touring the Swiss Alps with Agassiz he realized that the Alps and also the adjacent lowlands had been extensively glaciated in recent times. In 1838, Agassiz's *Discours de Neuchatel* was plucked from obscurity and published in English by Robert Jameson of the University of Edinburgh.[21]

In response, Charles Lyell presented a paper in 1839: *On the boulder Formation or drift and associated freshwater mud cliffs of eastern Norfolk.* In this report, Lyell described in detail a wide range of features including: *boulder clays*, *erratic boulders* transported from source rocks as far away as Scandinavia; freshwater arctic shell layers, and ***near contemporaneous contortions*** in these deposits.[22] These features are all symptomatic of glaciation given the benefit of hindsight today and they are also illustrated in the *Kosciuszko Photoglossary*.

Lyell accepted the evidence for a recent, very cold phase of climate based on fossils of arctic shells found at Norfolk. However, he attributed the deposition of the surrounding boulder clay to a phase of relatively deep submergence, allowing the long-distance transport of erratics, by icebergs from Scandinavia. Lyell suggested that the grounding of these icebergs produced the contortions in many of the deposits described at Norfolk, thereby explaining these features with his *modified diluvial model* (also referred to as Lyell's *glacial drift model*).[23]

The Icelandic, *Bruarjokull Project*, (2004) has demonstrated a large-scale process called ***glacio-tectonics,*** whereby the surging of ice-cap glaciers in Iceland's recent past has caused widespread disruption and contortions to sediment layers, deposited at the margins of these ice caps. This process explains the contortions and folding of glacial sediments on large and small scales, whereas the interaction of icebergs with large expanses of moraine above sea level is an implausible model and is unsupported by modern observation.

Uniformitarianism guides us to recognise processes and the resulting sedimentary structures that are active today, when interpreting structures and sediments in the rocks of past ages. Lyell's 1839 paper on glacial drift at Norfolk muddied the comprehension of glaciation as a global process for most of the 19th century. He was a great scholar but he may have been manipulated by those around him, as you will perceive in the next chapter. Lyell's *glacial drift model* failed the test of *uniformity of process through time* but it persisted as the main paradigm for glacial processes amongst English speaking geologists during the 19th Century.

Chapter Three Buckland's Plan B

This chapter describes Buckland's efforts to systematically research field evidence (of a prior widespread glaciation in the United Kingdom), and present the findings to the Geological Society of London, during the winter meetings of November, 1840.

In 1840 Buckland was working on ***Plan B***. He intended to use the upcoming Glasgow meeting of the British Association of Scientists in September, to bring Agassiz, himself and Lyell together, so they could investigate the Scottish Highlands for evidence of prior Continental Glaciation.

Buckland was reported to have said: **"never try & persuade ye world of a new theory persuade 2 or 3 of ye tip top men-& ye rest will go with ye stream".[24]**

Buckland's strategy was to convince Lyell of the validity of the Continental Glacial Model so that Agassiz, Lyell and himself could provide a united front, to present a set of papers to the Geological Society of London, describing evidence of past continental scale glaciation in Scotland and compare it to the evidence of prior widespread glaciation in Switzerland. After *The British Association* meeting finished on the 23rd of September, Buckland helped Lyell record evidence of past land-based glaciation in Scotland, beginning with Lyell's own estate, Kinnordy, near Forfarshire. In just one week from the 13th to the 20th of October, Lyell recorded in Notebook 84, 58 field drawings, sections and profiles plus detailed notes on 20 localities ranging from highland corries (cirques) to the sea. On October 13th Lyell, in his notebook, sets out his reasons for accepting that continental land-based glaciation was the only explanation to account for the sedimentary debris observed:

The entire absence of organic remains in these deposits.
The absence of significant stratification [layering] in debris which has been transported large distances.
The contortion of alternating layers of perfectly level gravel, sand and mud resting on layers which show little or no disturbance.
The striated and polished surface of many boulders.
The striated and polished surface of rocks in situ.
The local character of the boulders brought down different valleys.
*Frequent mounds or narrow ridges resembling terminal moraines***.**
The above reasons recorded in Lyell's notebook are consistent with the practices and premises of modern glaciology up to the present day.

During these few weeks of October 1840, Agassiz, Buckland and Lyell between them identified 117 localities in Britain, that presented clear evidence of recent widespread glaciation. The range of evidence collected by the trio included:

Fluvioglacial/outwash deposits	*33 sites*
Kame/kame terraces	*33 sites*
Terminal or lateral moraines	*28 sites*
Glacial polishing and rounding	*26 sites*
Till	*24 sites*
Erratics	*22 sites*
Striations	*21 sites*

Hummocky moraine	*20 sites*
Ice damming and drainage diversion	*11 sites*
Drumlins	*10 sites*
Grooves of bare rock surfaces	*9 sites*
Roches moutonnées	*8 sites*
Eskers and related features	*8 sites*
Glacial re-advance within a moraine	*1 site.*[25]

The above observations were verified by P.J. Boylan during 1981 and 1984. This catalogue is both fairly comprehensive in the range of glacial features described and very extensive in the area of terrain examined. Some of these features are illustrated with examples from northwestern Scotland, Yorkshire and Ireland in the *Kosciuszko Photoglossary*: *Striated Pavements*, *Abraded Landscapes* and *Cirques* as well as *Erratics, Roche moutonnées and Moraines.*

These three prominent geologists were now ready to present a body of evidence supporting *continental glaciation* of large areas of Scotland, Ireland and England to the members of the Geological Society of London, who gathered at Somerset House on 4th November 1840, for the winter program of meetings.

The meeting began with a reading of Agassiz's paper titled: *On glaciers, and the evidence of their having once existed in Scotland, Ireland and England.* Agassiz concluded *"**that great masses of ice and subsequently glaciers existed in these portions of the United Kingdom at the period preceding the present condition of the globe**,".*[26]

He argued that all the evidence pointed to an ice-sheet of Greenland proportions, not merely Alpine style valley glaciers that are seen in Europe today. This was a huge intellectual leap in the comprehension of the development of these landscapes. It was also a challenge to the conservatives who were quite comfortable and committed to the Diluvial model.

These conservatives were also having difficulties differentiating religious dogma from Scientific Method and were unwilling to re-evaluate any of their earlier work. Despite the well-reasoned papers and supporting evidence presented by Agassiz, Buckland and Lyell, the Geological Society of London only published edited versions of the abstracts of these papers in order to minimise their impact.

Buckland subsequently resigned the President's chair of the Geological Society of London so that he could defend this new model of Continental Glaciation against the conservative backlash and enter the fray from the ordinary debating benches.[27]

Lyell however, was shaken by the vehemence of the conservative backlash by senior members of the Geological Society of London, and although he submitted the full text of his paper for publication by the Society, it was never published let alone preserved. Lyell's application to the Geological Society requesting permission to withdraw his paper was approved and recorded in the Society's Council minutes of 5th May 1841. Meanwhile, the Council sat on the papers read by Agassiz and Buckland as it was unwilling to publish them and reluctant, or perhaps unable to reject them. Buckland broke the

deadlock by withdrawing his paper on 28th June 1842 and Agassiz' two papers were never formally accepted or rejected nor preserved for posterity; which appears to be a form of censorship.[28]

At the time of his death in 1875, Charles Lyell was one of the few geologists of his generation that went to his grave apparently rejecting most of the evidence for a recent large scale, continental glaciation covering Europe and the U.K.[29] ….. **Or did he**?

It is possible that Lyell was trapped by his conservative peers and publishers and could not credibly resurrect his work on continental glaciation undertaken in October, 1840.

Chapter Four Edgeworth David and the Hunt for Glaciation Downunder

This chapter describes Edgeworth David's early and ongoing interest in glaciation; his appointment to the chair of Geology and Physical Geography at Sydney University in 1891 and his close association with the Australasian Association for the Advancement of Science (AAAS). David was now primed to make sense of a series of prior reports on Australian Glaciation from Queensland, New South Wales, Victoria, Tasmania and South Australia leading up to the Federation of Australian States in 1901.

This *Diluvial* vs. *Glaciation* debate was still hot tearoom talk when T.W. Edgeworth David entered Oxford University in 1877, to study classics and follow in his father's clerical footsteps.[30]

It is not surprising that David became involved in geology, as his father and other family members were avid students of the natural sciences often rambling through the hills around their home in Cardiff, Wales. On the 17th November 1881, Edgeworth David presented his first paper or research article to the Cardiff Naturalists Society, titled: *Evidence of glacial geology in the neighborhood of Cardiff.* It was well received with the committee voting to publish his presentation in its proceedings complete with a lithographed map.

A second paper: *Evidence of glacial action in South Brecknockshire and East Glamorganshire,* was presented to the society on 9th August 1882. Based on the mapping of erratics, he showed the dispersal of ice in different directions out from the Brecon Beacons.

After a short period of study at the Royal School of Mines, in October 1882, David was appointed as Assistant Geological Surveyor to the New South Wales Geological Survey. By the 19th May 1891 his enthusiasm, charm and powers of observation assisted his appointment to the Chair of Geology and Physical Geography at the University of Sydney. Here he developed geology as a strong and popular discipline.[31]

Edgeworth David's long-term commitment to the Australasian Association for the Advancement of Science (AAAS), lead to a thorough review of evidence for Ice actions or Glaciation in Australasia. The 1895 AAAS report on *Evidences of Ice Action in Australia and Tasmania,*[32] started with the 1859 report by R.C. Selwyn on glaciation at Inman River, south of Adelaide in the driest state of the driest continent. In 1866, Selwyn, Daintree and Wilkinson reported boulder clays at Bacchus Marsh, Victoria with exotic clasts and pebbles that had grooves typical of glacial action, as well as fossils of Gangamopteris longifolius.

Professor Ralph Tate reported in 1877 the glaciated rock pavements of sculpted, striated and polished quartzite at Hallett's Cove, 15 miles (24km) south of Adelaide. [Refer to Kosciuszko Photoglossary: *Permian Glaciation* for some illustrations of glaciated bedrock pavements at Hallett's Cove and Kangaroo Island].

Then in 1879, R.L. Jack reported large boulders of granite, slate, schist and quartzite in the Permo-Carboniferous coalfield of the Bowen Basin in Queensland, which he interpreted as erratics.

By 1885, R.M. Johnson had reported ice borne erratics embedded in Permo-Carboniferous sediment on Maria Island, off the eastern Tasmanian coast.

These reports on Permo-Carboniferous glacial evidence in Qld, NSW, Vic & Tas as collated by David, must have been confounding at first because **no extensive, prior glaciation was known beyond Europe and North America at that time**. These known glaciations in Europe were also restricted to the relatively recent past few million years of the Pliocene and Pleistocene.

In the nineteenth century, scientists did not have the ability to calculate absolute ages of strata, as the technique of radiometric dating using radioisotopes had not been developed. Instead, they used **relative time** by comparing fossils in a succession of strata and geologists identified characteristic or index fossils to specify relative age in a succession of strata.

By the late 19th Century, geological time was subdivided by the succession of fossil plants and animals into three main Eras. The Palaeozoic or Ancient-life era was oldest, followed by the Mesozoic or Middle-life era, with the youngest, the Cainozoic or Recent-life era.

Eras are sub-divided into Periods, and further sub-divided into Epochs. The last period of the Cainozoic Era is the Quaternary, subdivided into the Pleistocene Epoch, (starting about 2.5 million years ago) representing the last Ice Age, with the Holocene Epoch (starting at about 15 000 years ago) with the transition to warmer conditions.

In his 1914 book on *Australasian Fossils*, Frederick Chapman describes the Permo-Carboniferous Epochs of the Upper Palaeozoic Era as typified by a sudden appearance of ferns of the Glossopteris type. The tongue shaped fronds of Glossopteris have reticulate venation or network veins (figure 4.1), while the related Gangamopteris is characterised by not having a distinct mid-rib and has fan-like venation.[33]

These plant fossils are also found in India, South Africa, South America and the Falkland Islands. This wide distribution of such ancient ferns indicates that these now isolated land-surfaces were once connected to form an extensive super-continent. Prof Eduard Suess called it, “Gondwanaland” from the Gondwana district of India, which is illustrated in figure 4.2. In 1885, Suess however did not have a clear concept of how the pieces in the Gondwana jigsaw fitted together.

In 1890 Dr Ottokar Feistmantel of the Indian Geological Survey correlated the Bacchus Marsh Beds in Victoria with the Upper and Lower Marine Beds of Newcastle, NSW and in addition correlated both of these beds with the Dwyka Conglomerates of South Africa and the Talchir Beds of India.[34]

In 1890, E.J. Dunn, a Victorian Mining Surveyor also confirmed the above correlations and gave a detailed description of the glacially abraded nature of blocks and cobbles in the Bacchus Marsh and Wild Duck conglomerates as well as the Dwyka conglomerates of South Africa. However, in his conclusion published by the AAAS, 1890 he states on p456: “*No other conclusion can be arrived at than that floating ice has been the agent by which the material has been brought into its present position*.” Lyell’s ***glacial drift theory*** was still alive and well in 1890 Australia.

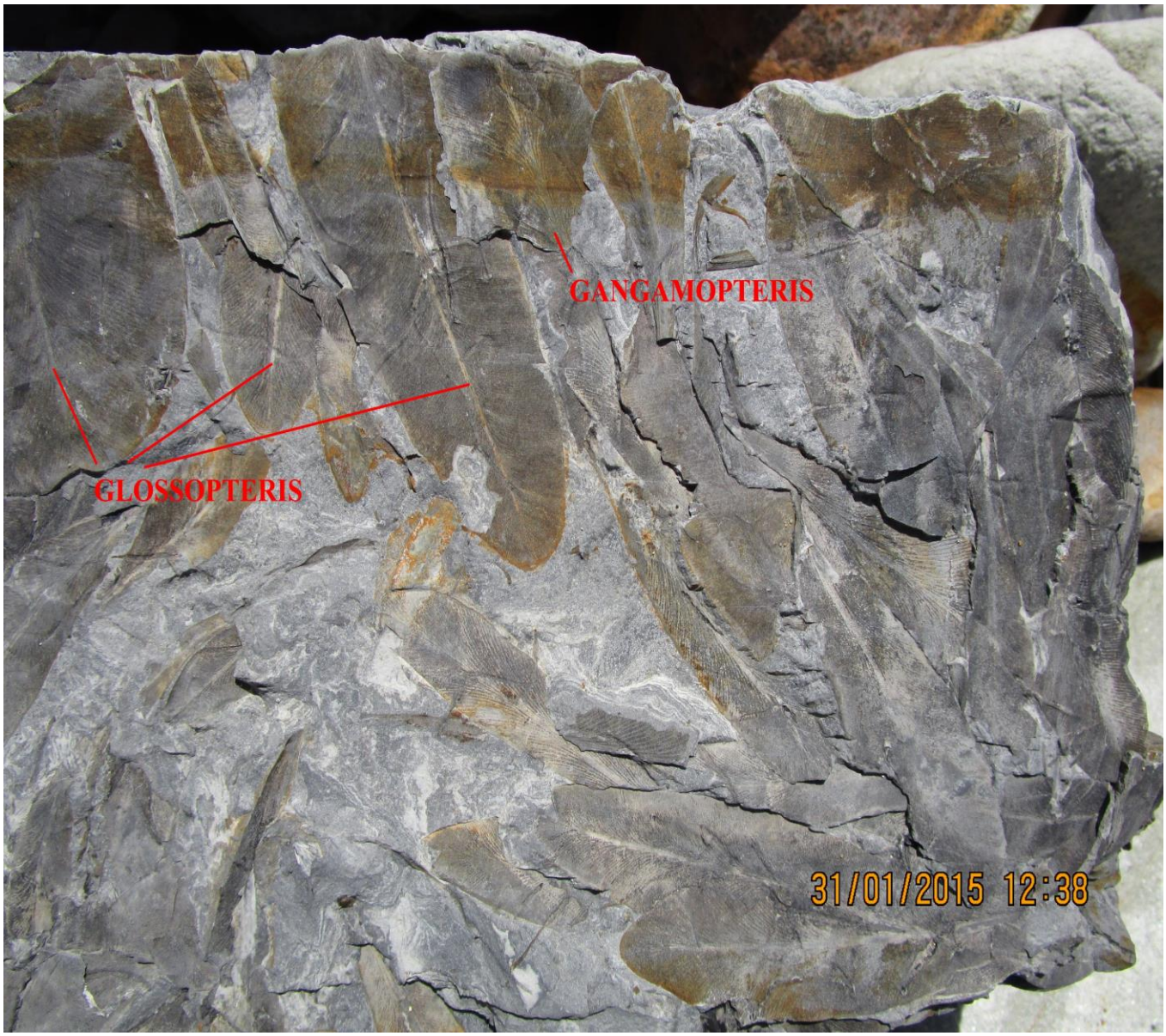


Figure 4.1 **Most of these leaf-like structures appear to be Glossopteris**, because they have a mid-vein. Photograph taken by Tom Keelty.

This correlation of Permo-Carboniferous sediments (including coal and glaciated sediments) across three continents, paved the way for fitting the pieces of the Gondwana Puzzle together and underpinned the concept of Continental Drift developed in the 20th Century.

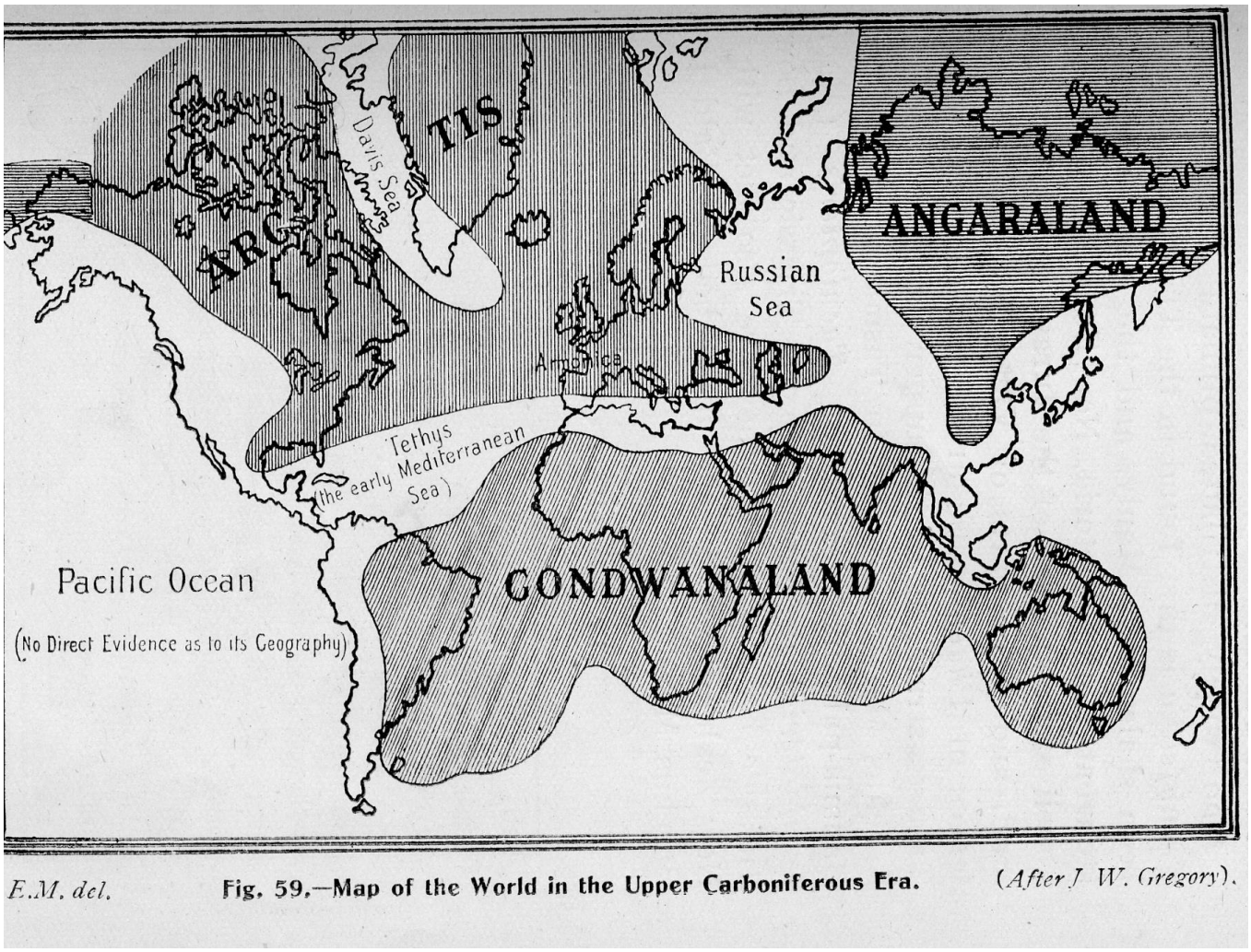


Figure 4.2 Representation of Gondwana taken from ***Australasian Fossils: A Student Manual of Palaeontology***, by Frederick Chapman, published by George Robertson & Company P. L., Melbourne, 1914.

Chapter Five Another Farmer to the Rescue

This chapter acknowledges the role of another farmer/scientist: Charles Clifton Brittlebank who wrote to TWE David on 4th December, 1894 with a radical opinion. David investigated C. C. Brittlebank's conclusion concerning evidence of Palaeozoic glaciation at Bacchus Marsh and in his report to the AAAS in 1895 he was able to characterise and differentiate evidence of widespread Permo-Carboniferous continental glaciation in Australia from more recent evidence of glaciation in the Highlands of Victoria and New South Wales.

One young observer who had participated in many of the detailed investigations of the Bacchus Marsh Permo-Carboniferous glacial deposits, was not convinced by the *Diluvial Model* which was still in use by all senior geologists employed by various State Geological Surveys in Australia at that time. His name was Charles Clifton Brittlebank. He wrote to Edgeworth David on the 4th December 1894 about his conclusions on the nature of glaciation at Bacchus Marsh. Brittlebank, a dairy farmer at Bacchus Marsh was also a gifted illustrator and mycologist, (student of fungus). In his view, during the late Palaeozoic or early Mesozoic:

"....land ice came from the SSW to the NNE. This was either a continuation of the Antarctic Ice Cap or immense glaciers from land south of Australia".[35]

This clearly implied the existence of a large land mass to the south of Victoria in Permo-Carboniferous time. This was an extraordinary proposition at the time. Together with Ottokar Feistmantel's proposition of large-scale glaciation across the southern portions of three continents (India, Africa and Australia), Brittlebank's proposition would not be fully appreciated for another seventy years when the concepts of Continental Drift and Plate Tectonics provided the context and probable mechanism to explain large crustal movements.

At this time, Edgeworth David was in a difficult position as he attempted to resolve differing opinions on the nature of Permo-Carboniferous glaciation, as well as differentiating the ancient Permo-Carboniferous glacial evidence from the more recent glaciation, reported in the highlands of New South Wales, Victoria and Tasmania.

He resolved the character of the Permo-Carboniferous glaciation as being a large-scale Continental Glaciation which had been closely associated with fossils such as Glossopteris and Gangamopteris. David concludes his discussion of Permo-Carboniferous glaciation in Australia with: ***"The thickness and extent of its Palaeozoic glacial beds stands as yet without a rival in any part of the world. Let anyone who questions the accuracy of this statement follow the advice of that grand old geologist Desmarest, and "Go and see".***[36] Edgeworth David then turned his attention to the more recent looking glacial evidence from the Highlands which he summarized in 1895.

David summarised and queried prior reports, reporting that:"***glaciers near Kosciuszko in the Australian Alps descended to about 5 200 feet above sea level*** *[*1585mASL*]. In Victoria near Mt Bogong, at Mountain Creek Valley morainic material (?) extends down to a level of 2000 feet asl* *[*610m*] and possibly only 1000 feet in the Reewa* *[*Kiewa*] Valley.*[37]*" "Glaciated surface (?) on Mt Bogong.*[38]*"*

James Stirling (1886) had reported evidence of glaciation on Mt Bogong and glacial moraines in the Kiewa Valley after an expedition with Robert von Lendenfeld but was queried by David in 1895. Stirling also reported possible moraine dammed lakes on the Livingstone Creek near Omeo,[39] which was subsequently dismissed. Subsequent geological investigations in NE Victoria by F.C. Beavis in 1959,[40] also refuted prior evidence of glaciation on Mt Bogong and the Bogong High Plains.

Chapter Six Boulders, Boulders Everywhere but not an Iceberg in Sight

This chapter title alludes to the Merchant of Venice and the ongoing saga of the Glacial Drift theory during the late 19th Century. It is also a warning not to jump to conclusions concerning the genesis of sedimentary debris without carefully examining particle morphology, bedding characteristics, and the context of the depositional environment.

James Stirling's 1886 report states in part: *"Notes on Mt Bogong.....In the Mountain Creek valley, at the northern base of Mt Bogong..... large masses of angular and waterworn masses of rock are strongly suggestive of distributed or scattered moraines and are hardly conceivable as talus derived from the mere weathering of the northern escarpments some miles distant".*[41]

In 1986, I examined sediments along the margins and tributaries of the upper Kiewa Valley, many of which exhibit ***relict alluvial fans***. Alluvial fans are an important depositional feature formed at the change in slope of these steep valley sides. When occasional heavy rainfall events wash debris down a poorly vegetated steep slope, the water slows down as it reaches the change in slope at the edge of a valley. Slower water can carry less sediment, so the debris is deposited usually in a fan shape that broadens down-slope. The coarse bouldery material is deposited first near the fan head. Alluvial fans are built up by a sequence of intermittent *debris flows* and *sheet floods* and *stream floods* over a long period of time.[42] These processes are not active under the present climate in our Highlands, because the steep slopes above these relict alluvial fans are now well vegetated surfaces.

Mountain Creek drains the northern slopes of Mt Bogong (1986m) and flows west into the Kiewa River. Its catchment covers approximately 87km² with the main axis now draining through a relict alluvial fan, down 12km of valley floor.

The section of Mountain Creek Valley downstream of the 420m contour has deeply dissected bouldery sediments down as far as the 340m contour where the fan terminates against the Kiewa River Flood Plain. Both the Mountain Creek Valley and its alluvial fan steepen and narrow upstream towards the junction of Sodawater and Doorway Creeks. This intersection is the apex or head of the alluvial fan with the terrain rising very steeply further upstream. The sediment exposed near the head or apex of this alluvial fan is made up of boulders embedded in a red, sandy clay matrix which is consistent with it being a *debris flow*.

Since deposition, these boulder-sand-clay sediments have been eroded by Mountain Creek and the feeder streams, leaving only the large boulders as a lag deposit in the stream bed, near the head and also in the adjacent terraces. Cuttings through elevated portions of the old alluvial fan expose the original debris flows. This erosion began during the Holocene when the climate became wetter and warmer and regular water flow in Mountain Creek excavated fine debris within its channel. Massive lag-deposits of waterworn boulders, 0.5m to 1.2m diameter, have accumulated along the floor and margins of upper Mountain Creek. Refer to the *Kosciuszko Photoglossary*: *Alluvial Fans* which illustrates sections along Mountain Creek and alluvial fans in general.

These bouldery, lag-deposits can easily be misinterpreted as remnant or reworked glacial moraines. However, their position below a sudden change in slope; their distribution in tributary valleys feeding into the Kiewa River; their rounded to angular clasts or rocks, and the rapid decrease of clast size and sediment texture towards their lower ends, at 340m; mark them as an alluvial fan complex.

There is also an absence of striations or faceting in the included cobbles. This alluvial fan complex is currently being dissected and so is probably a relict or remnant feature with respect to the present climate and vegetation. A modern brown loam soil horizon, has also formed above the alluvial fan deposits which suggests they formed prior to the Holocene when most of our top-soils have developed.

So, the report by James Stirling in March 1886 which noted a large accumulation of angular and waterworn masses of rock in the valley of Mountain Creek, needs to be considered as probable evidence of an alluvial fan rather than as remnant glacial deposits.

These alluvial fans were probably active during the Pleistocene when vegetation on the steep valley sides was suppressed. Alluvial fan activity would have been accelerated by an arid climate with reduced temperatures. Both aridity and cold conditions would have suppressed local vegetation growth. This would have left the northern slopes of Mt Bogong bare and vulnerable to sporadic flood events, causing mobilisation of surface debris down-slope as *debris flows*.

The absence of fresh evidence of glacial erosion or deposition on the elevated surfaces of Mt Bogong and the Bogong High Plains is also consistent with cold but arid conditions during cold phases of the late Pleistocene.[43]

However, there is evidence from several sources of massive, angular deposits of basalt, granodiorite and rhyodacite on the Victorian Highlands above 1400m, some of which have been dated as late Pleistocene.[44]

These deposits above 1400m formed of open angular blockwork, appear to be *cryogenic* and are indicative of cold dry conditions with minimal accumulation of snow. There is also a similarity between the lag deposits at the apex of these relict alluvial fan deposits of the mountain valleys, and the open blockwork deposits above 1400m which is compounded by their genesis in that they both required arid conditions to be active.[45]

These deposits probably existed as a sequence during the late Pleistocene with alluvial fans collecting debris from catchments reaching up to the lower edge of the blockwork terrain (near 1400m) and depositing their debris on valley floors adjacent to the Bogong High Plains.[46]

The same sequence of blocky deposits prevails on the Kosciuszko Plateau and its marginal terrain, so that the investigations into these cryogenic deposits on the Bogong High Plains are relevant to unravelling the Ice Age Heritage at Kosciuszko. There are exposures of alluvial fan debris near Island Bend, adjacent to the Snowy River at 1200m asl, on the flanks of the Kosciuszko Plateau. These are discussed and illustrated in chapter 9 which considers palaeoclimatic evidence.

The next chapter recounts Edgeworth David's systematic investigation of the Kosciuszko Plateau in 1901.

Chapter Seven Game-On

This chapter describes David's 1901 expedition to Kosciuszko and the range of evidence collected. David, Helms and Pittman reported glacial evidence associated with small cirques, possible valley-glaciers and possible ice-cap glaciation. This chapter introduces the concept of provenance or source of sedimentary debris. Browne and Vallance (1957) used this argument for debris found in the catchment of Spencers Creek to suggest that glacial ice had once surmounted Charlotte Pass from the Snowy Valley. R. W. Galloway (1963) attempted to rescind this argument with rather dubious generalisations regarding the authenticity of glacial erratics identified by David (1901), (1908), and Browne and Vallance (1957), (1963).
As a result the game is very much still-on.

By 1897, David had accumulated a set of short reports on the Kosciuszko region: Clarke 1859, Von Lendenfeld 1885, Helms 1889 & 1895, Jaquet 1895 and Kitson and Thorn 1897. None of these reports presented a systematic search for evidence of glaciation and some of the reports found no evidence of glaciation at all near Kosciuszko. Edgeworth David was champing at the bit to "***go and see"*** Kosciuszko and let nature do the talking.[47]

So in February and March of 1901, David, Helms, Pittman and Guthrie examined a large portion of the Kosciuszko Plateau and found clear evidence of ice action including:

Smoothing of rock surfaces
Roches moutonnées
Grooved and striated rock surfaces and striated boulders
Erratics and perched blocks
Terminal and lateral moraines
Lakes and tarns of glacial origin.[48]

David, Helms and Pittman presented a detailed report to the Linnean Society of NSW on the 27th March 1901, which included an exhibition of lantern views, colored diagrams, glaciated boulders, rock specimens and microscope rock sections. When the report was published on the 13th August 1901, it contained eight plates which included photographs and plans and sections of the areas studied in detail. Plate iii is partially reproduced as figure 7.1.[49]

Before reading further, look at the Kosciuszko Photoglossary: *Main Bedrock units at Kosciuszko,* to help your visualisation of the landscape and your understanding of the rock types. The main types of bedrock found in the Kosciuszko area are mapped on the 1990 Geology of Kosciusko National Park Map. A *Glacial Features Inset map* published with this map provides an overview of the glacial features and bedrock boundaries near Kosciuszko despite some errors and omissions, and it is presented as figure 7.2.

David, et al (1901) examined each of the lakes and their surrounds starting with Cootapatamba, located in a south trending, broad, trough-shaped valley to the south of Kosciuszko. Near Rawson Pass at 2120m, referred to by David et al as *Ramshead Pass,* they observed ice-smoothed rock surfaces and moraine material, with occasional ice-scratched blocks from 7150 feet (2179m) on the Etheridge Ridge, down the valley towards Lake Cootapatamba. The few boulders showing glacial markings were fine grained feldspathic quartzite of Unit ***Of***, but not the coarse granite material of Units ***gab21*** or ***glw7***.

Figure 7.1, shows the disposition of the main rock types accurately, with all the granitic rocks unshaded and the metamorphic rocks of unit ***Of*** listed as Slates and shown with cross hatching in their plate iii. The inner and outer moraines adjacent to Lake Cootapatamba are clearly drawn and listed as the upper and lower terminal moraines respectively. Note the location of the north trending belt of metamorphic rock which strikes beneath the moraine adjacent to the lake and occupies the east side of the valley between the lake and Ramshead Pass [Rawson Pass on current maps].

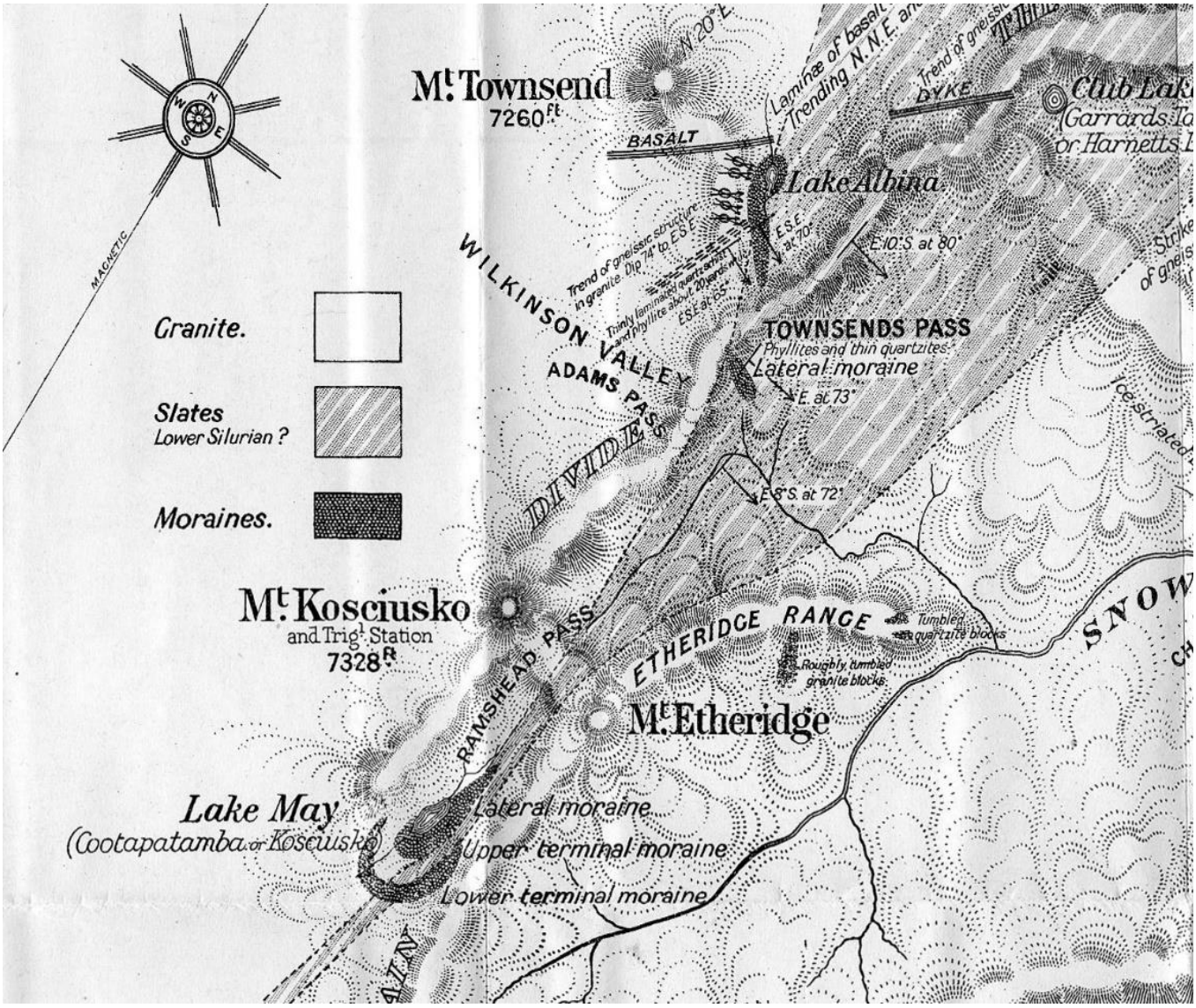


Figure 7.1 is **portion of plate iii, David et al 1901**. It shows the co-linear valleys of Cootapatamba-Rawson Creek-Lake Albina. They share a contiguous snow fence extending SSW and NNE from Kosciuszko.

This sketch map is more accurate than the currently published map reproduced as figure 7.2 which shows this band of metamorphic rock displaced about 300m east of its true position, relative to the drainage lines. The uppermost Swampy Plain River runs along the western contact of this band of metamorphic rock unit (***Of***) from its outcrop below Rawson Pass for at least two kilometres downstream. Its location is important because we have to recognise and account for the provenance of the erratics in order to make sense of the glacial processes.

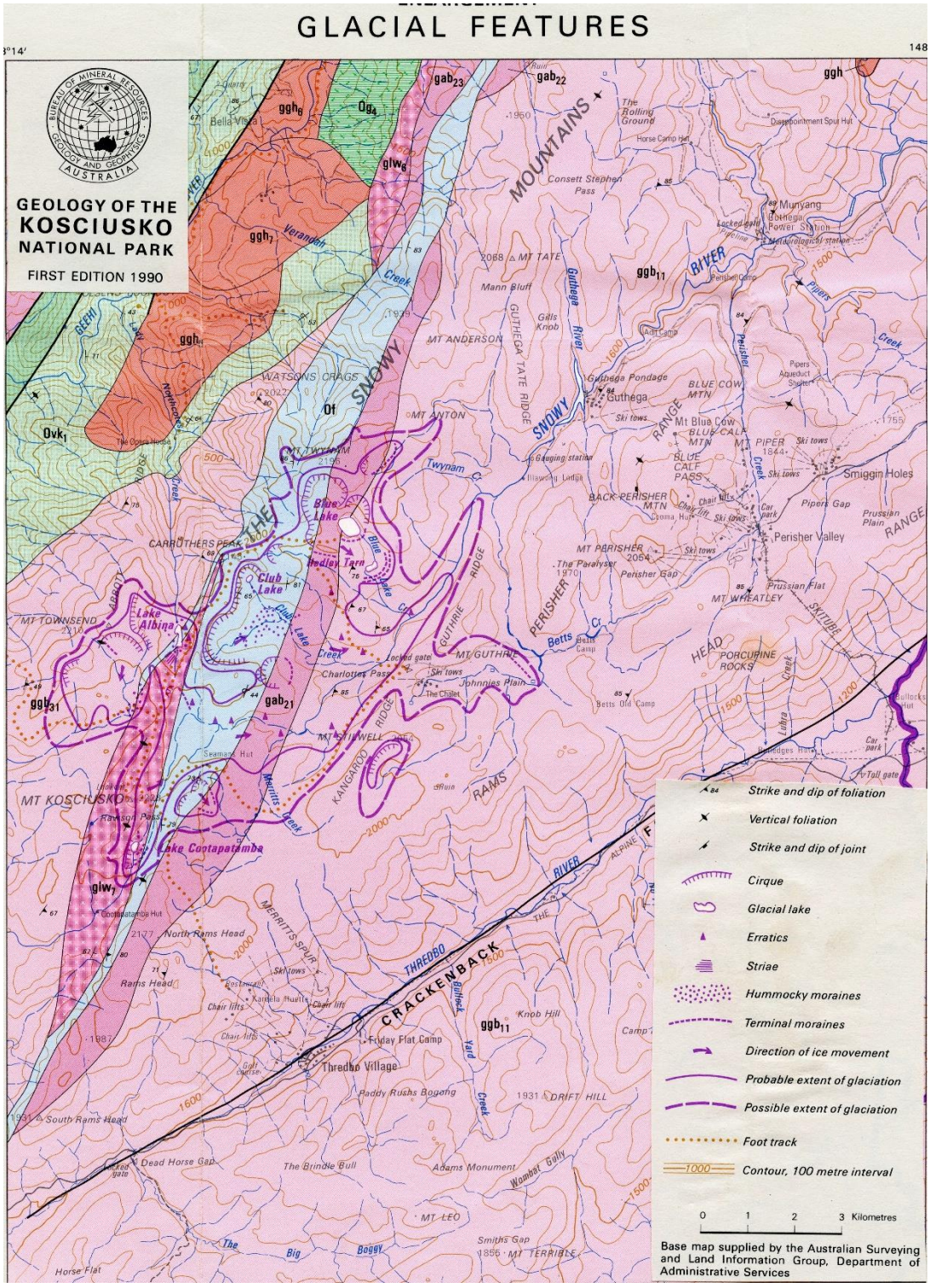


Figure 7.2 **Glacial Features Inset Map**, Geology of Kosciusko, 1990.

This inset map was reproduced from "Geology of Kosciusko National Park, 1990" by the BMR, with permission. The glacial evidence above is an exact reproduction of Galloway's (1963) figure 6. See endnote 139 .

John Dulhunty (1945) followed in the footsteps of Edgeworth David and undertook a systematic series of soundings in order to obtain bottom contours of the four main glacial lakes in the Kosciuszko area. His aim was to determine the depth of glacial debris damming these lakes and also determine the level of the solid bedrock beneath the moraines and adjacent lakes. Both David et al (1901) and Dulhunty recorded the thickness of the inner moraine wall at Cootapatamba as 21-24m and the outer moraine wall was estimated as 55m thick. The outer moraine wall which has been breached by the Swampy Plain River is about 500m downstream of the inner moraine. Dulhunty's cross-section (figure 7.4) suggests that ice movement was in the direction of A-B on his plan (figure 7.3), which is toward the E.S.E.[50]

The ridge running S.S.W. from Kosciuszko acts as an effective snow fence trapping large volumes of snow on its steep, east facing slopes in the lee of the prevailing winds. During the Late Pleistocene Ice-Age, the accumulation of snow and ice along this slope would have pushed downwards and south-eastwards, carrying with it bits of granitic bedrock and debris from the Kosciuszko south ridge behind Lake Cootapatamba. This debris was eventually pushed up into a wall, with Lake Cootapatamba forming behind it, and is referred to as the inner moraine.

The fact that there is an inner and outer moraine wall indicates at least two periods of glacial activity in the recent past. The outer moraine may have once had its own lake before its wall was breached. Both the inner and outer moraine are relatively well preserved, suggesting that this small-scale glacial action occurred in the recent past.

The provenance of the glacial debris adjacent to Lake Cootapatamba was reported by David et al (1901) as: *"the blocks of moraine are nearly all granite, mostly from 3 feet up to 8 feet in diameter…occasionally up to 12 feet in diameter*".[51] This writer examined exposures of the outer moraine adjacent to the breach and could only observe granitic debris. The inner moraine is dominantly granitic rock with a few metamorphic blocks scattered along its distal margin. The source of this granitic debris is the steeply sloping ridge running south from Kosciuszko, which forms the western back-wall to Lake Cootapatamba. This provenance reinforces the direction of ice movement towards the E.S.E. from the steep granitic back-wall behind the lake which is further illustrated in chapter 8.

The plan and section produced by John Dulhunty, illustrate a very shallow lake with the dominantly granitic debris pushed up onto metamorphic bedrock as shown in figures 7.3 and 7.4. Dulhunty's assessment was that: *"the lake originated from moraine-damming rather than over deepening of the U shaped valley*".[52]

This then begs the questions: *"What caused the U shaped valley below Rawson Pass and when?*" {Refer to figure 7.5 which illustrates this valley upstream of Lake Cootapatamba}; and *how did these metamorphic blocks get incorporated into the Cootapatamba moraines?*. Chapter 11 considers the evidence for a prior ice-cap and valley glaciers at Kosciuszko.

A curious observation by David et al was: *"the best ice-scratched blocks obtained by us were at the base of the [*inner*] terminal moraine near its east end*.[53]" Also: *"Such few boulders as exhibit glacial markings*

are of feldspathic quartzite, and were derived from the east side of the valley"[54]. Clearly, David et al considered in 1901, that these terminal moraines near Lake Cootapatamba were produced by a small valley glacier flowing southwards from Rawson Pass rather than resulting from a southeastwards push off the Kosciuszko South Ridge. However, there was probably **no** significant source of snow and ice at or north of Rawson Pass unless there was an ice field several hundred metres thick capping Kosciuszko; and that would have produced a more extensive terminal moraine across the entire valley with its wall oriented across the valley floor, not parallel to the drainage line as is its present condition.

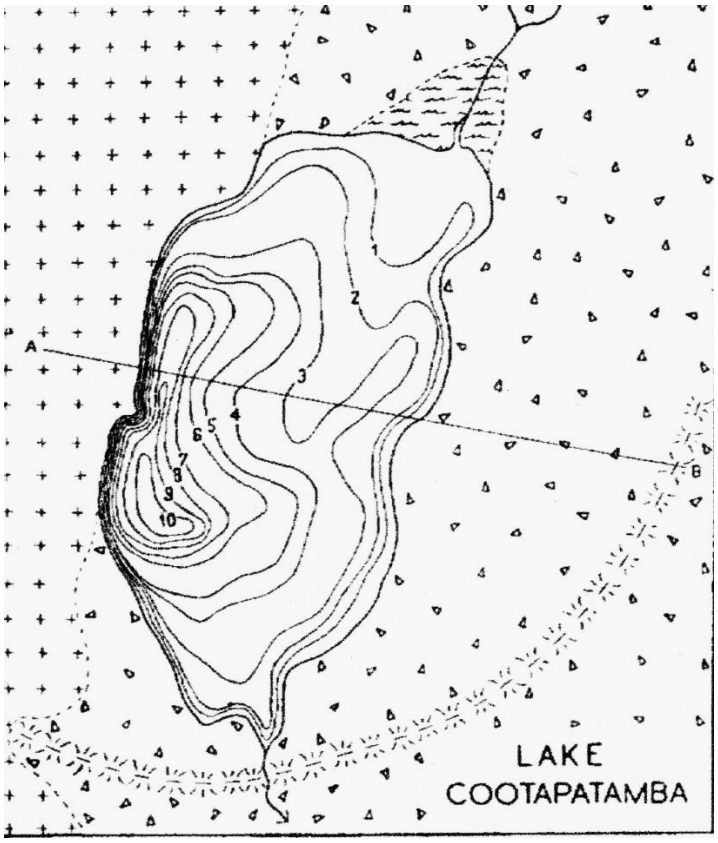


Figure 7.3: **Plan View by John Dulhunty of Lake Cootapatamba**. Depth contours are in feet. Hatching shows the distal edge of the Inner Moraine.
A-B shows location of cross-section in the following figure 7.4.

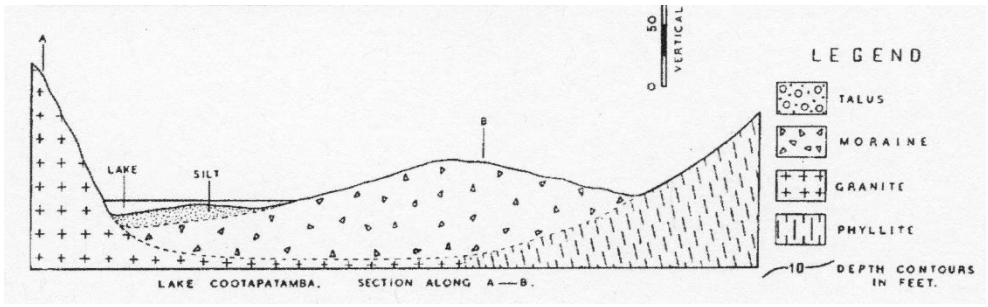


Figure 7.4 **Cross-Section through Lake Cootapatamba** by John Dulhunty, 1945.
The above figures (7.3 & 7.4) were reproduced from their original publication:
Proceedings of Royal Society of NSW., **79**:143-152, 1945.

In addition to the erratics noted by David et al in the distal margins of the inner moraine, this writer has observed occasional blocks of metamorphic rock on top of the granitic moraine just beyond the waters edge, near the eastern edge of the lake. These cannot be easily explained by eastward movement of ice and debris off the Kosciuszko South Ridge because there is no metamorphic bedrock on the Kosciuszko South Ridge nor eastwards down the sides as far as the central drainage line. This suggests that they may have been reworked from large-scale glacial activity prior to the late Pleistocene.

David et al, (1901) made a cursory examination for a short distance below the level of the older, outer breached moraine, at Cootapatamba but collected no further evidence of valley glaciation below this point; but they did not rule out the possibility of an earlier and more extensive valley glaciation. What do you think? These questions are examined in chapter 11. David et al, (1901) went on to describe paired moraines associated with Lake Albina and Blue Lake and their findings are discussed in chapter 8, *The Kosciuszko Moraines.*

In 1956, W. R. Browne submitted that up to 1000km² of terrain above 1450m on the Kosciusko Plateau had been subjected to glaciation which he visualised as having occurred in three stages of decreasing intensity: {Ice-Cap, Valley Glaciation and lastly Cirque-Style Glaciation}.[55] He based his model on broad geomorphic features including: cols, roches moutonnées, truncated spurs and cirque-like depressions as well as depositional evidence of moraines.

This paper was followed with an investigation by W. R. Browne and T. C. Vallance in 1957 which described evidence to further support Browne's 1956 paper. However, in their discussion of depositional evidence supporting the former Ice-Cap they describe this ground (the Kosciuszko Plateau) as: "*liberally bestrewn with boulders and blocks of granite in a gritty matrix, notably on some west facing slopes. This appears to be at most a veneer on solid granite, and where runnels of thaw-water have been formed down a slope the matrix has been completely washed away and a belt of boulders resting on each other* [imbricate texture] *with empty spaces between has been formed simulating the appearance of a rock river*".[56] The above description of "moraine" by Browne and Vallance is totally consistent with *relic, cryogenic, vegetated blockslopes and blockstreams* which are best developed on elevated slopes of the Kosciuszko Main Range, in granitic terrain with a western aspect. This aspect may be coincident with the prevailing wind which would have minimised snow cover on the windward side and would also have maximised radiative cooling leading to ***frost shattering*** and localised ***cryogenic sorting*** associated with ***permafrost***.

The west side of Kosciuszko is illustrated in Chapter 9 (Fig 9.9) and the west side of Mt Townsend is illustrated in figure 7.6 below. This writer considers that Browne and Vallance 1957 have mistakenly mapped *relict cryogenic debris* as *moraine* over large areas of the Kosciuszko National Park. This overstatement of a prior ice-cap glaciation at Kosciuszko probably triggered R. W. Galloway to make a re-appraisal of the situation in 1963.

Galloway recognised that some of the moraines described by Browne and Vallance had been confused with "*solifluction features such as stone streams, block fields, stone banked lobes and stone banked*

Figure 7.5. **View from the distal end of Lake Albina upslope towards Rawson Pass**.
The centre of the col above in Rawson Pass is 1000 m NNE from the view point of figure 7.5. The intervening landscape is consistent with John Dulhunty's description as a U shaped valley.

terraces".[57] This writer agrees with Galloways' general proposition. Blockfields, blockslopes and blockstreams in the Kosciuszko area and elsewhere in southeastern Australia are discussed in chapter 9.

Galloway also stated that "*It is difficult to distinguish true glacial till from the unconsolidated deposits resulting from weathering and solifluction particularly in granitic areas* [where] *deposits consist of a heterogeneous mixture of boulders and stones in a gritty matrix*".[58]

However, Galloway seems unaware of the textural signature of cryogenic blockwork or the possibility that some older moraines may have been reworked by the same processes that generated the stone streams and block fields he referred to when discussing moraines.

Figure 7.6. **View from Mt Townsend toward Jagungal** at rear and right of view. The western slope in the midground is littered with frost riven and stepped granodiorite bedrock and collections of open blockwork. This terrain has been subjected to deep seated *frost shattering*, *frost creep* and *frost-heave*.

However, in attempting to refute all possible evidence of large-scale glacial abrasion, including the evidence of hard, fine grained rocks (like quartzite), possessing polish, faceting and striations; Galloway has stretched his own credibility. On page 193 of his 1963 paper Galloway states: "***Striations or faceting of the stones are not reliable indications of a glacial origin since these features can also be produced by mass movement, slickensiding and joint planes***." Tectonic movement of bedrock along joint planes will cause shearing and sometimes cause a veneer of powdered rock on the joint surfaces. This thin sometimes striated veneer is known as ***slickensides***. It is a fragile veneer of finely powdered rock which weathers quickly when exposed unlike the excavated scratches and gouges we see developed as

striations on sub-rounded, fine-grained glacial debris and bedrock surfaces. This is discussed further in chapter 11 and in particular is illustrated in Figure 11.4.

This writer seeks to describe the *Kosciuszko Moraines* associated with the small cirque-like glaciers of the Kosciuszko Main Range during the last glaciation, in chapter 8. It is very important to appreciate their common characteristics as a starting point, in order to differentiate them from any older glacial evidence that lurks beyond the relict cirques of the Kosciuszko Main Range.

Then in chapter 9 we consider evidence of ***cryo-conditioning*** and ***permafrost*** which appears to have been widespread in the highlands of southeastern Australia above 1000m during the late Pleistocene, and particularly during the last cold phase or Last Glacial Maximum. These cryogenic processes were dominant during prior cold phases of the late Pleistocene and their palaeoclimatic associations are developed and discussed in chapter 10, which helps explain why glaciation decreased in intensity during the late Pleistocene to the extent that only 15km² of the Kosciuszko Main Range was glaciated during the last glacial maximum (LGM) as described by Barrows et al in 2001.

However, the conclusion that: "***there is no well preserved evidence of older or more extensive glacial events***…[beyond the]… ***two main phases of glaciation, best represented by the inner and outer moraines at Blue Lake,*** *(Barrows et al 2001)***"** is an ongoing reason for **Game-On**.

Chapter Eight The Kosciuszko Moraines

This chapter describes the characteristics of two sets of small, paired moraines associated with restricted, cirque-style glaciation of the late Pleistocene, collectively referred to as the ***Kosciuszko Moraines***. They conform to the definition of moraines and they contain clues to their relative age which Edgeworth David described in detail during 1901.

In 1908 after a second expedition, Edgeworth David summarised his view of the glacial evidence at Kosciuszko very succinctly and his model satisfies all the evidence discovered by this writer.
Other researchers including R.W. Galloway (1963) and Barrows et al (2001) have confused the evidence and failed to differentiate the relatively recent, small-scale *Kosciuszko Moraines* from the much older and more widespread glacial evidence at Kosciuszko.

The other important point to this chapter is that the cosmogenic radiometric exposure dating carried out by Barrows et al (2001) only gives consistent dates for the inner Kosciuszko Moraines which formed during the last glacial maximum but also provides direct confirmation of permafrost and cryo-conditioning during the late Pleistocene rather than an accurate assessment of the timing of glacial activity earlier than the last glacial maximum.

Moraine is a term which has been in use since the 18th century to describe glacial debris accumulated at the snout or muzzle of a glacier. There are many forms of moraine but the common meaning is: *an accumulation of glacial debris which is visible due to its relative relief against the local terrain*. The outermost ridge formed at the limit of a glacial advance, is known as a *terminal moraine* and the younger moraines nestled within it are termed *recessional moraines*. These curved elevated mounds of debris which accrete at the margins of a glacier, are very distinctive landforms which have been used diagnostically, to identify prior glacial activity in the Kosciuszko landscape. The other term used to describe glacial debris is *till,* which refers to: *a layer or veneer of glacial debris spread over a wide area by the base of the moving glacier*. These features are illustrated in the *Kosciuszko Photoglossary*.

Elevated ridges over 2000m asl in the Kosciuszko area, with a NNE-SSW orientation which could intercept the prevailing westerlies during the Pleistocene, accumulated snow on their lee sides. During the late Pleistocene, these ridges as well as small cirques and cirque-like depressions, acted as a locus for the accumulation of snow and ice, which then pushed debris outwards to form small moraines at short distances from these sites of ice-accumulation. The *Kosciuszko Moraines* mapped by this writer and illustrated in figure 8.1 below, form paired sets of inner and outer moraines. In every case, the debris in the outer moraines has subdued relief and appears to have been reworked; the end result being a higher frequency of large blocks or open blockwork at the surface, in comparison to the inner moraines. The inner moraines maintain their glacial fabric with blocks and cobbles surrounded and supported by a gravelly sandy matrix, and supporting a well vegetated surface. The condition of the outer moraines associated with cirques at Kosciuszko, suggests a time-gap or hiatus after their deposition, prior to the last glacial episode which produced the still well-preserved inner moraines.

In the figure 8.1 below, the outer moraines associated with the restricted cirque-like glaciation at Kosciuszko, are outlined with orange dots, and the inner moraines are outlined with yellow dots. Professor David's expedition in 1901 mapped and described the moraines associated with the relict cirque-lakes of Cootapatamba, Albina and Blue Lake. This writer has added Mawson Cirque, Twynam East Cirque and Rawson Creek Cirque to David's work. The moraines in Wilkinsons Valley are not included in figure 8.1 yet, as mapping is not fully resolved.

R. W. Galloway (1963)[59] included 13 relict cirques and minor cirque-like features on his figure 6 but confused his model by not discriminating evidence of an earlier ice-field/valley glaciation from this later, very restricted cirque-style glaciation. In addition, Galloway (1963) failed to recognise the paired terminal moraines at the very head of the Snowy River, associated with Rawson Creek as shown on my figures 8.1 and 8.6 below. Now we can return to David et al (1901) and their description of these *Kosciuszko Moraines*.

David et al (1901), were the first to recognise and map the inner and outer terminal moraines at Lake Cootapatamba. David wrote: "*The lake which is about one quarter of a mile long and has a maximum depth of about 17 feet, is bounded, at its lower end, by a very well marked terminal moraine*", shown in figure 8.2; a reproduction of his plate iii; and also figure 8.3. "*While the length of the terminal moraine does not exceed one quarter of a mile, its height, at this east end, is a little over 40 feet, and near the*

centre about 75 feet. … *The blocks in the moraine are nearly all granite* [unit **glw7**]*, and are mostly from 3 feet up to about 8 feet in diameter. … It was only on the east side of the moraine that fragments of phyllite and quartzite* [unit ***Of***] *were found. … At a total of about 22 chains*[440m] *below the south end of Lake May* [Cootapatamba] *is a second terminal moraine, obviously older than the preceding.*"[60] Refer to the *Kosciuszko Photoglossary* for additional illustration and description of cirques and rock-types at Kosciuszko.

An overview of Lake Cootapatamba and its surrounding terrain has been produced by annotating a Google Earth image and is presented as figure 8.4, below. This oblique view looking northwards up the valley of the Swampy Plain River shows the distal margins of the inner and outer moraines as red dots and red dashes respectively. David et al regarded the northeastern extension of the moraine adjacent to Lake Cootapatamba as a lateral moraine. This writer considers that the thin discontinuous moraine extending up the eastern side of the valley is an attenuated extension of terminal moraine which has been pushed across the valley from west to east. Black dashes illustrate approximate displacement pathways for the ice and debris sliding off the Kosciuszko South Ridge.

A curious observation by David et al noted: *"the best ice-scratched blocks obtained by us were at the base of the* [inner] *terminal moraine near its east end*." Also: *"Such few boulders as exhibit glacial markings are of feldspathic quartzite, and were derived from the east side of the valley*".[61] Clearly, David et al considered that these terminal moraines near Lake Cootapatamba were produced by a small valley glacier flowing southwards from Rawson Pass.

An ice-field over Mt Kosciuszko could have produced a valley glacier moving southwards from Rawson Pass and produced a more extensive terminal moraine across the entire valley, with its wall oriented across the valley floor, not parallel to the drainage line as is its present position. Galloway (1963) appears to have made the same assumption as David et al (1901) and/or, not recognised the contradictory evidence.

The late Pleistocene glacial events at Cootapatamba would have bulldozed pre-existing *regolith*, or rocky debris including any *erratic* metasediment blocks, outwards to the E.S.E., incorporating them into the inner and outer moraines of Cootapatamba. This suggests that an earlier more extensive glaciation may have carved this U-shaped valley and also deposited the quartzite blocks with tell-tale striations, close to their present positions, prior to the late Pleistocene. The late-Pleistocene glacial activity responsible for pushing up the inner and outer moraines here, would have incorporated any pre-existing glacial debris in their pathway which could explain these apparently anomalous fragments of metamorphic rock sitting on the rim of Lake Cootapatamba.

The next area traversed by David et al was Rawson Creek which descends NNE from Rawson Pass down to its intersection with the Snowy River. This creek runs parallel to the massive NNE trending ridge from Kosciuszko which still acts as an effective *snow fence,* like its extension to the SSW which had acted as a *snow fence* for the relict cirque, Lake Cootapatamba, illustrated in figures 8.3 & 8.4.

Cirque number 5 referred to by Galloway (1963),[62] on the southeast flank of Muellers Peak is not a cirque but rather a small component of the 2.3 km long NNE trending ridge/*snow-fence* from Mt Kosciuszko to Muellers Peak. It was this 2.3km snow fence that fed snow into Rawson Creek and the uppermost Snowy Valley which terminated with paired inner/outer moraines as per the enlarged extract of the Kosciuszko Glacial Debris Map shown below as figure 8.6. This is very similar to the collection and sliding of ice off the ridge to the SSW of Kosciuszko which dozed and deposited the moraines against Lake Cootapatamba, discussed above and illustrated below.
David et al described the "*Smoothed* [bedrock]*surfaces of quartzites were observed by us between the head of the valley* [of Rawson Creek] *and the small recent landslip",*[63] [at GR 142659]. The disposition of the Rawson Ck moraines is consistent with ice sliding eastwards off the entire 2.3 km snow fence adjacent to Rawson Creek.

The large remnant moraine below and south of Albina Pass [Townsend pass as described by David et al]; is the uppermost part of the *Rawson Ck outer moraine,* which then trends ESE for 640m. Towards its distal end, it reduces to smoothed low relief terrain, with irregular hummocks for a further 400m, before terminating as a crescent of scattered erratic granitic boulders and shallow debris, across the valley of the Snowy River near GR148663.

Large, pale granitic erratics (unit ***glw7***) continue up the opposite valley side and terminate at GR 146662 as shown by orange dots on figure 8.6. These blocks have moved upslope for a short distance just prior to deposition and they are located 700m beyond their closest bedrock outcrop. The *inner Rawson Creek moraine* is hummocky on the northern side of the valley (see figure 8.5 below), and contains multiple circular pits consistent with thermokarst, like the inner moraine at Cootapatamba. It degrades downstream into a thin sheet of bouldery debris towards the southern side of the valley. This writer recorded striations along 075°MB and faint gouges along 085°MB near GR143667. This location and striae bearing is shown with a red arrow on figure 8.6. Further downstream the gps recorded the location of the many large, pale adamellite erratics (unit ***glw7***), where they had terminated near GR 148663, in a tight arcuate band and thereby defining the distal *outer moraine;* associated with ice flowing out of Rawson Creek, and shown on figure 8.6, with orange dots.

David's group next examined the Albina valley north of the Albina Pass. At the upper end of the Lake Albina valley, they describe the inner moraine as: *"the valley is filled with hummocky masses of moraine material, surmounted by large granite erratics up to 20 feet in diameter"…*and "*several small tarns are situated* [in this moraine] *near the upper end of the moraine debris, south of Lake Albina*".[64] This inner moraine is shown in figure 8.8. The *tarns* or (small ponds) are significant because the depressions they occupy were caused by the melting out of ice trapped in the moraine after the glacier receded with the advent of warmer conditions.
These depressions (or *thermokarst*), get filled in over-time and their presence indicates that this inner moraine is relatively recent like the inner moraine at Cootapatamba, which is also imprinted with circular depressions or thermokarst, as is the smaller inner moraine associated with Rawson Creek.
The distal or outer moraine at Albina was described by David et al as: "*moraine drift has been carried beyond the north end of Lake Albina, and to some height up the eastern slope of the valley*".[65] This outer

moraine is characterised by its high frequency of large granitic blocks at the surface and its low relief, as observed by David et al (1901). This can also be seen in figure 8.8, (northeast of the lake) which presents an overview of the Albina valley looking towards the northeast. There is also a hint of several remnant terminal ridges in this attenuated relatively low-relief, outer-moraine (shown as yellow dashes), which suggests there were several still-stands during the regression of glacial ice responsible for the outer moraine at Albina relict cirque as well as recessional ridges within the inner moraine.

This writer agrees with David et al, and has mapped the distribution of these different moraines as the inner and outer moraines in figure 8.7. The outer moraine at Lake Albina has probably been reworked by *frost-heave* which has preferentially pushed the largest blocks upwards through the enclosing debris and created an imbricated blockfield, which is evident throughout this outer moraine. *Imbrication* is a textural term which is illustrated in the *Kosciuszko Photoglossary*. A *blockfield* is a broad area of gentle-moderate gradient covered (with at least 50% cover) by coarse open blocky debris.

The abrading action of ice was noted on bedrock surfaces by David et al at Lake Albina as: *"the grooves and striae are so fresh on some of them as to appear to be of quite recent origin*".[66] The trends of these abrasions are also marked on figure 8.7 as well as Davids plate (iii) 1901 presented as figure 8.2.

This easterly trend across the main axis of the valley is similar in style and direction to the glaciation reported at Lake Cootapatamba and in both cases it cannot have contributed to the U-shaped cross-section of these valleys in which these moraines reside. Sculpted valleys with a U-shape cross-section require glacial abrasion directed down the main axis of the valley, not across the valley.

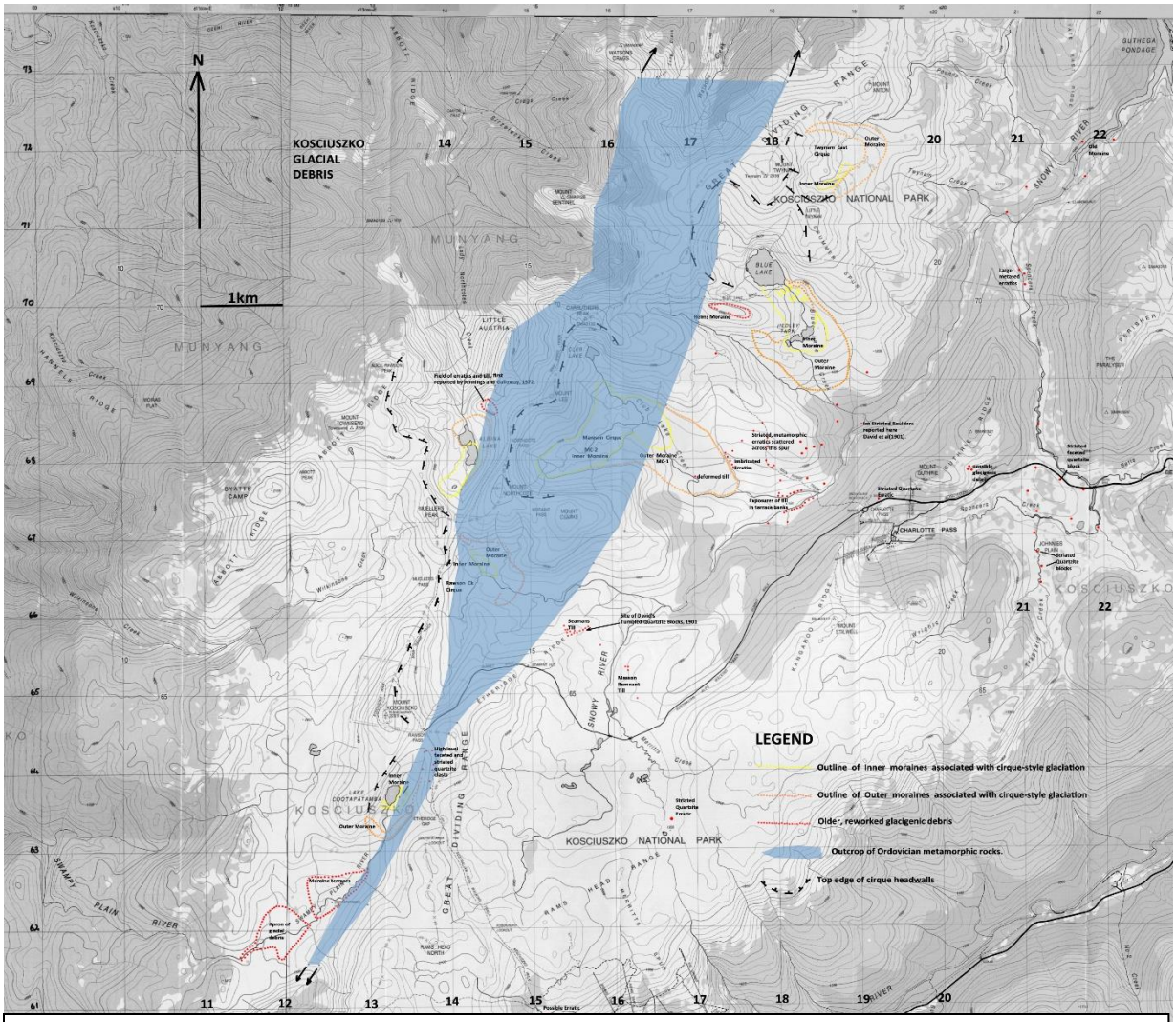


Figure 8.1 Kosciuszko Glacial Debris Map

The Kosciuszko Moraines of the late Pleistocene are shown as paired inner moraines (yellow dots) and outer moraines (orange dots). The red dots show areas or spots where much older glacial debris has been located.

The blue overlay shows the distribution of metamorphic bedrock of unit ***Of*** mapped by this writer.

The black, dashed form-lines mark the upper edges of snow-fences/cirque walls above evidence of late Pleistocene moraine.

Base map extracted from Perisher Valley 8525-2S and Youngal 8525-3S topographic maps copyrighted to Department of Lands, NSW (2001), with permission.

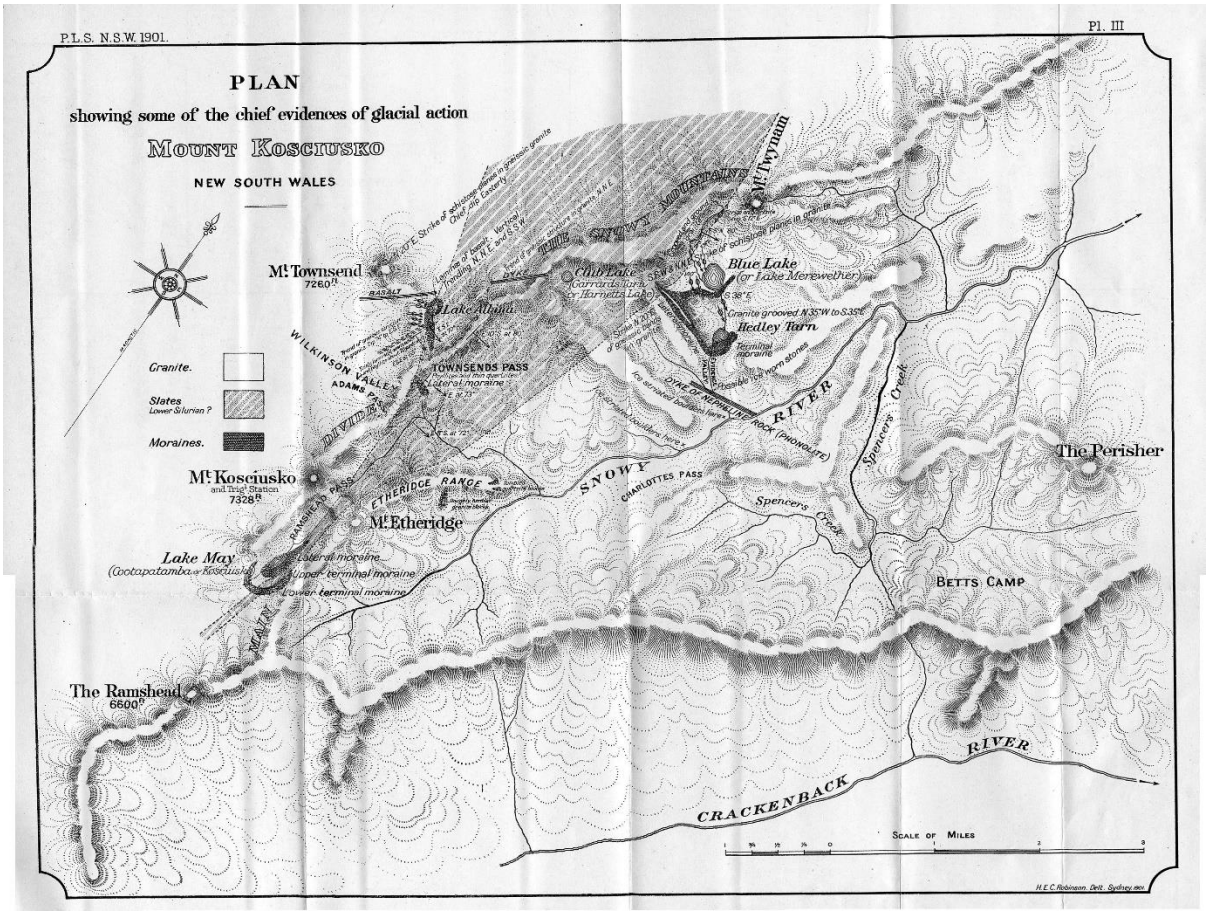


Figure 8.2

David et al 1901. Plate iii

This figure was copied from an autographed original copy of the paper:
Geological Notes on Kosciusko, with Special Reference to Evidences of Glacial Action. From: Proceedings of the Linnean Society of New South Wales, 1901, part1, March 27th, by; Professor David, Richard Helms and E. F., Pittman.

Figure 8.3 **View over Lake Cootapatamba from the northeast, in late spring**. The Southern Ridge from Kosciuszko extends 1000m from Kosciuszko summit. Note that the inner moraine is a composite structure with snow-filled linear hollows between overlapping sheets of moraine, evident in the right-hand half of the inner moraine wall. Also note the small shallow ponds towards the inner edge of the inner moraine, which are thermokarst depressions. The outer moraine buttresses up against the Kosciuszko Ridge several hundreds of metres south of the inner moraine and tapers or attenuates as it hooks around and continues up the centreline of the valley. Also, within the buttress zone of the inner moraine, there appears to be three separate threads to this inner moraine (separated by snow), which compliments the three ridges comprising the inner moraine, which are evident to right side of figure 8.3, complete with thermokarst depressions, now filled with water. This structure of composite moraines is consistent with what we see at Blue Lake, despite the reduced magnitude at Cootapatamba and is contrary to the observations and comments by Barrows et al 2001.

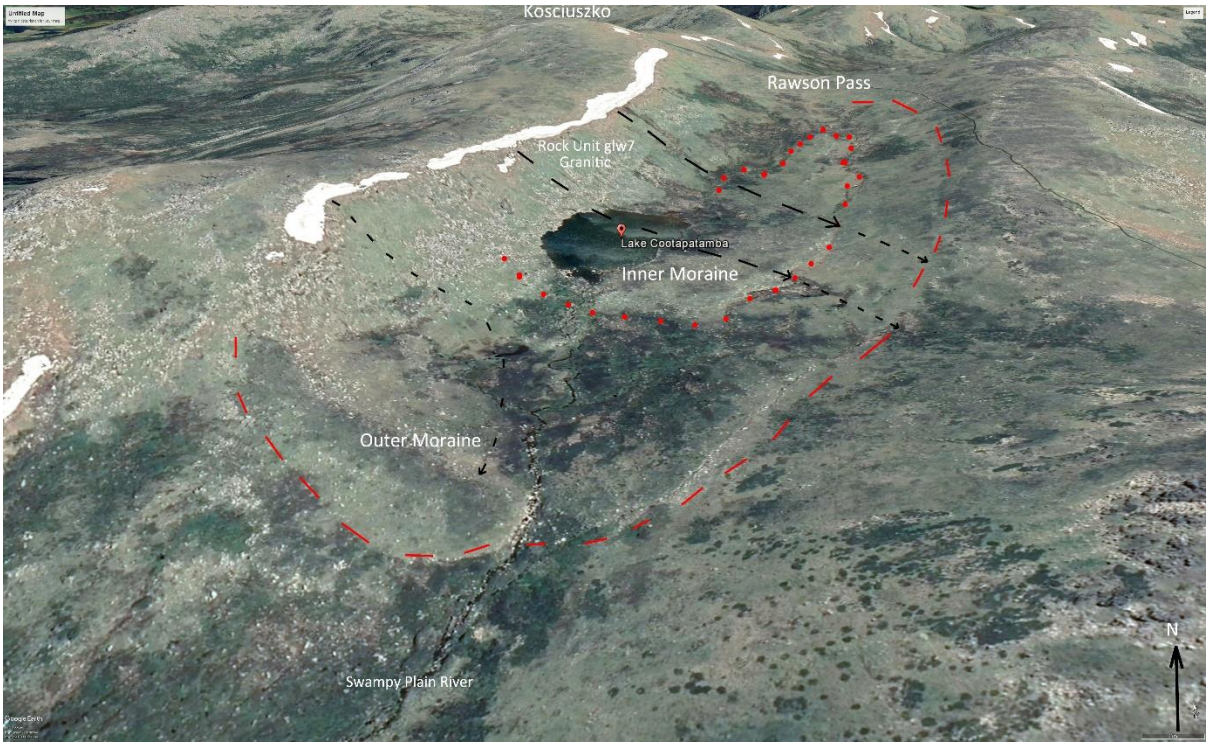


Figure 8.4 **Oblique satellite view of Lake Cootapatamba**. Red dots mark the inner moraine and red dashes mark the outer moraine. Black dashes show very approximate pathways for ice sliding off the Kosciuszko South Ridge. Detailed mapping of erratics in this valley is presented in Chapter 11. *Google Earth, imagery dated 26/12/2018, accessed on 3/9/2019 © 2019 CNES/AirBus*

Figure 8.5 **Distal end of inner moraine from Rawson Creek Glacier**. Rawson Ck intersects with the uppermost Snowy River near the tents at right of view. This inner hummocky moraine contains a depression in foreground at right (thermokarst), and a veneer of pale granitic blocks continues across the valley floor to the south, with the bedrock here being of unit ***Of*** (metamorphic rock).

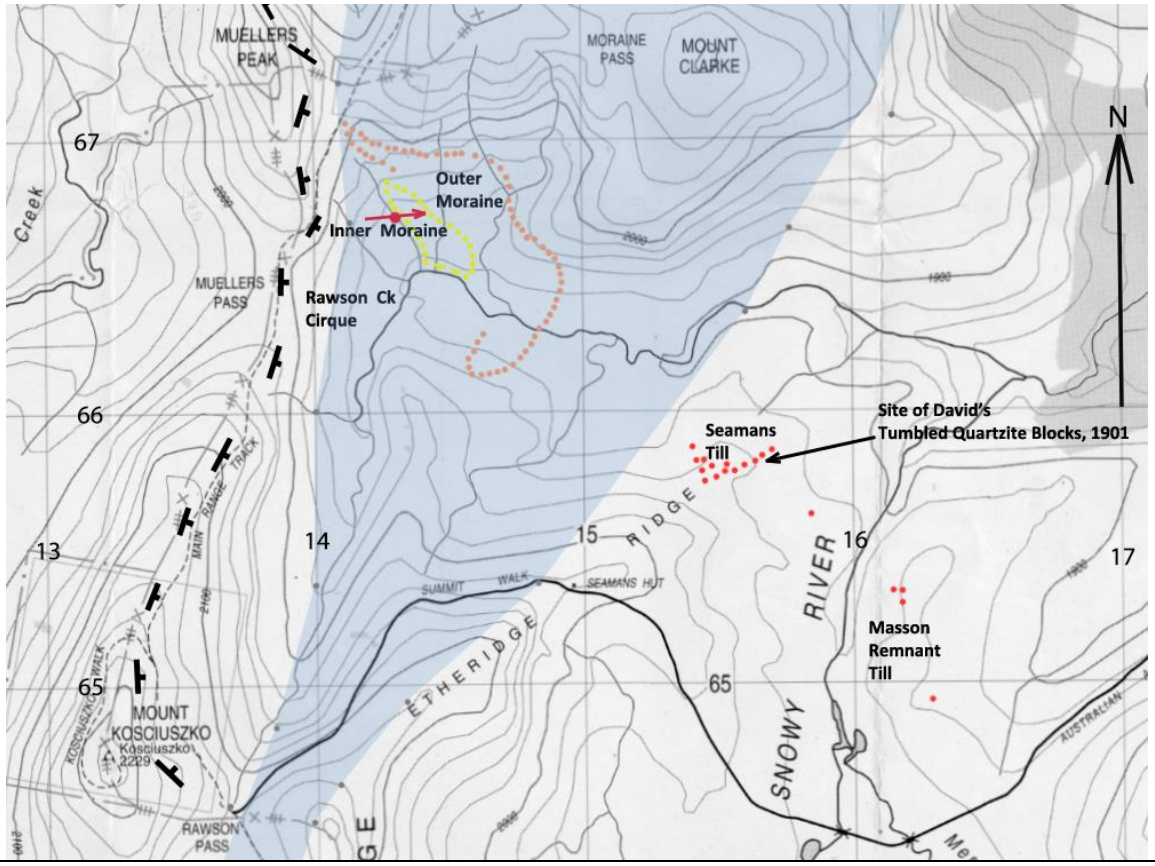


Figure 8.6 **KOSCIUSZKO GLACIAL DEBRIS MAP** centred over the uppermost Snowy River to show details of Rawson Ck Moraine.

Note that the debris associated with the Rawson Creek glacier is dominantly pale coarse gneissic adamellite of unit ***glw7*** from the Kosciuszko Ridge and the underlying bedrock is metamorphic rock of unit ***Of***.

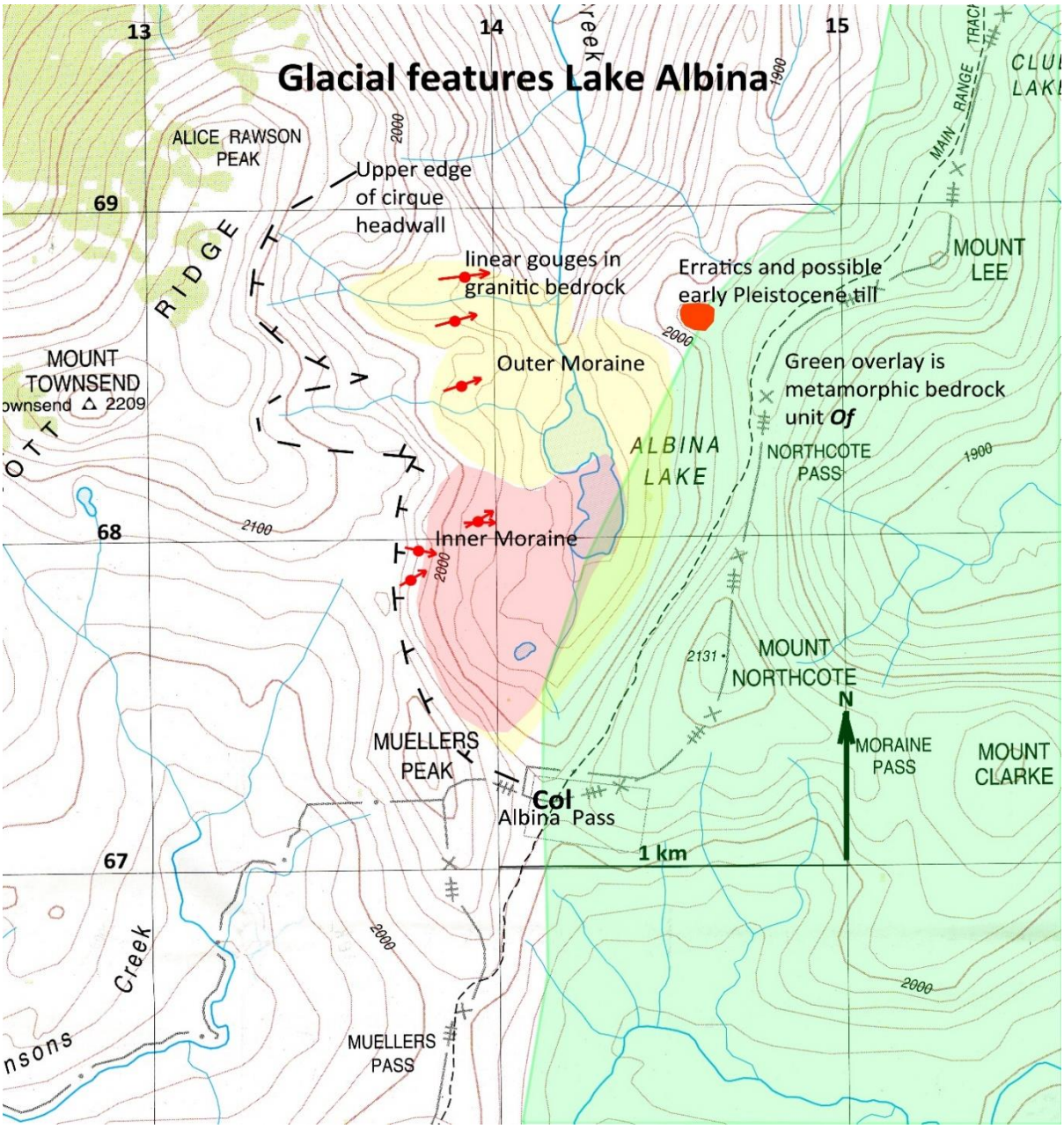


Figure 8.7

Lake Albina Late Pleistocene Glaciation

Yellow overlay (at 20% opacity) represents the outer moraine.
Red overlay (at 20% opacity) represents the smaller inner moraine.
Red arrows represent striae or gouges in the granitic bedrock.
The **green overlay** represents the distribution of metamorphic bedrock of unit *Of*.
The **black form lines** depict the upper edge of this small compound cirque.

Figure 8.8

View northeastwards over Lake Albina moraines from Muellers Peak.

Yellow dots represent the outline of the distal edge of the *outer moraine*.
White dots represent the outer edge of the *inner* (hummocky) *moraine*.
Dashes represent ridges of debris.
Note the compound nature of these moraines and the thermokarst (ponds) in the foreground.

Moving northwards along the Main Range to Evidence Valley, David et al (1901) reported the largest and most complete moraine yet observed. They reported four closely packed terminal moraines, damming Hedley Tarn below Blue Lake in Evidence Valley. They also noted that much of the bedrock having been; "*powerfully ground down and grooved by moving glacier ice*",[67] in the valley between Hedley Tarn and the much larger Blue Lake upstream. These surviving grooves and polished surfaces suggest that the inner moraine adjacent to Hedley Tarn is relatively young. Figures 8.2 and 8.9 illustrate the distribution of debris in the vicinity of Blue Lake. These moraines are similar in style to the relatively small moraines described at Lake Albina, Rawson Creek and Lake Cootapatamba, despite the deeply carved cirque at Blue Lake, which has been eroded 27m below lake level into solid rock.

In summary, in 1908 Edgeworth David considered that: *" possibly 200,000 years ago, Kosciuszko was gradually covered by great fields of neve and glacier ice, and all but the very highest peaks of the plateau, such as the Nunatakr of the Etheridge Range, were completely shrouded in the ice-cap. The snow-field moved chiefly in a SE direction, pouring its ice over what is now a precipitous escarpment leading down into the Thredbo Valley. … Next we find in far more recent geological time, perhaps removed by only 10,000 to 20,000 years from the present, evidence of a fresh and conspicuous glaciation.* [This timing was calculated from estimated rates of erosion.] *Lakes Cootapatamba, Albina, Club, the Blue Lake and Hedley Tarn were formed during this epoch. Even this latest glacial epoch is divided into two, if not more stages* [and]*…..there is distinct evidence of a double series of terminal moraines on either side of the main dividing range."*[68]

In 2001 Barrows et al reported that the Blue Lake valley contains the most detailed glacial stratigraphy, including four terminal moraine ridges. They considered the outermost, flat-crested moraine (BL-I) below Hedley Tarn, is the oldest of these terminal moraine ridges. The inner series of three distinct terminal ridges (BL-II, BL-III, BL-IV) lie in sequence behind the outermost moraine. According to Barrows et al, Moraine BL-III truncates the BL-II moraine and converges with the BL-IV moraine which shows that the inner moraines are younger, which is also supported by their well-defined ridge-like form. The outer moraine (BL-I) on the other hand is not only flat-crested, its debris has been modified to produce a higher frequency of large blocks at the surface with an imbricate texture as evident in figure 8.10, similar to the outer moraine at Lake Albina. This imbrication and flattening is evidence of some downslope movement and spreading, which has occurred since deposition.

This writer considers that the moraine ridges adjacent to Hedley Tarn (BL-IV, III) and illustrated in figure 8.11 comprise the inner moraine at Blue Lake because these ridges are unmodified by cryogenic (freeze-thaw) processes; they maintain an abundance of gravelly, sandy matrix on their vegetated surfaces; and they are closely coupled with clearly defined thermokarst.

The other poorly defined bands of moraine BL-II and BL-I are considered as phases of the outer moraine because of their cryogenic modification into imbricated *blockfield terrain*. The description of the outer moraines by David et al: "*there is not now much sandy material between the blocks, which, on the lower side of the moraines, facing the Snowy River, form a rugged belt of huge boulders, difficult to traverse even on foot, the deep hollows being largely concealed from view by a growth of shrub",*[69] is a classic

description of a ***block field*** *or* ***block glacis***. Refer to figure 8.10. Block accumulations like this have a strong association with *permafrost and cryo-conditioning*. See *Kosciuszko Photoglossary: Cryogenic Evidence,* for more explanation.

This cryogenic modification of the outer moraines could only be achieved by long term exposure to very cold and very dry conditions, since being emplaced by the small cirque glacier at Blue Lake. What quantitative evidence do we have for the age of these moraines?

Barrows et al (2001) used a radiometric technique called *cosmogenic exposure dating* to measure the time span that a given rock surface has been exposed to the sky. They selected the moraines at Blue Lake and Lake Cootapatamba because they considered that only these moraines displayed discrete inner and outer moraines. They considered that the moraines at Club Lake and Lake Albina did not possess relatively older, outer moraines like those observed at Cootapatamba and Blue Lake. This writer does not agree with that interpretation and figures; 8.7 (Lake Albina), and 8.12 (Mawson Cirque), illustrate an alternate view based on detailed field mapping. The exposure ages obtained by Barrows et al (2001) confirm the geomorphic evidence at Blue Lake but contradict it at Lake Cootapatamba. However, according to Barrows et al, the exposure ages obtained on the oldest moraine below Blue Lake, (BL-I) "*scatter beyond the limits of experimental error".*[70] A summary is presented below.

MORAINE	Corrected Exposure Ages x1000 years
BL-I	45.3, 59.3, 39.9
BL-II	30.8, 34.2, 31.4
BL-III	20.6, 18.0
BL-IV	16.2, 15.6, 19.5
LC-I	17.0, 18.8
LC-II	17.3, 15.7, 17.7

Note that LC-I is the older, outer moraine at Lake Cootapatamba and LC-II is the inner moraine, hence the contradiction. In order to overcome this contradiction, they suggested that "*boulders may have been exhumed from beneath till since the moraine was deposited",*[71] but they did not offer a mechanism. This is a reasonable interpretation of the data, but what could be the logical cause of such exhumation? In this environment, the only logical candidate is *frost heaving* which is a well-researched phenomenon in ***permafrost terrain,***[72] but not active under present conditions.

The close proximity between the exposure ages of BL-IV, BL-III, LC-I and LC-II is not just coincidence and is also not evidence for simultaneous glacial activity. The geomorphic evidence absolutely negates the possibility that the inner and outer moraines at Lake Cootapatamba are the same age. The exposure ages for inner moraines: LC-II and BL-IV & III, suggest they were active at the same time and the geomorphic evidence supports that because they are both unaffected by cryogenic modification and they have sharply defined ridges with thermokarst pits. These inner moraines are typical of the most recent glacial activity during the late Pleistocene at Kosciuszko.

The question remains: What activated the dated blocks in the outer moraines at Cootapatamba (LC-I) to become exposed at the surface during the same time span that both the inner moraines (BL-IV, III and LC-II) were developing; and why is there such a wide spread in ages for the outer moraines at Blue Lake?

These tiny cirque-style glaciers on the Kosciuszko Main Range are evidence of very restricted precipitation leading to relatively small accumulations of ice associated with the cirques.
The total area affected by late Pleistocene glaciation has been estimated by Barrows et al as 15km². This writer has calculated an area of 16 km² for the extent of late Pleistocene cirque-style glaciation based on personal field mapping.[73] In other words, most of the elevated terrain in the Kosciuszko region was free of ice at the surface during the late Pleistocene. Minimal snow cover and cold conditions accelerate radiative cooling and this in turn promotes the development of ***permafrost***.

The anomalous exposure ages for the LC-I moraine and the 20,000 year spread of exposure ages at Blue Lake for the BL-I moraine is **supporting evidence of repeated cryogenic frost heave and movement in a permafrost zone at both Blue Lake and Cootapatamba during the late Pleistocene**. The imbricated arrangement of blocks in the outer moraines at Blue Lake and Lake Cootapatamba is also evidence of fluidity and downslope displacement.

The inner moraines at both sites, BL-IV, III and LC-II have similar, tightly constrained exposure dates and their surfaces seem unaffected by cryogenic modification whereas the massive spread in exposure ages for the outer moraines probably represents multiple episodes of cryogenic reworking between 20ka and 60ka before present. I would expect to find similar results if the outer moraines at Mawson cirque and Lake Albina were ever tested.

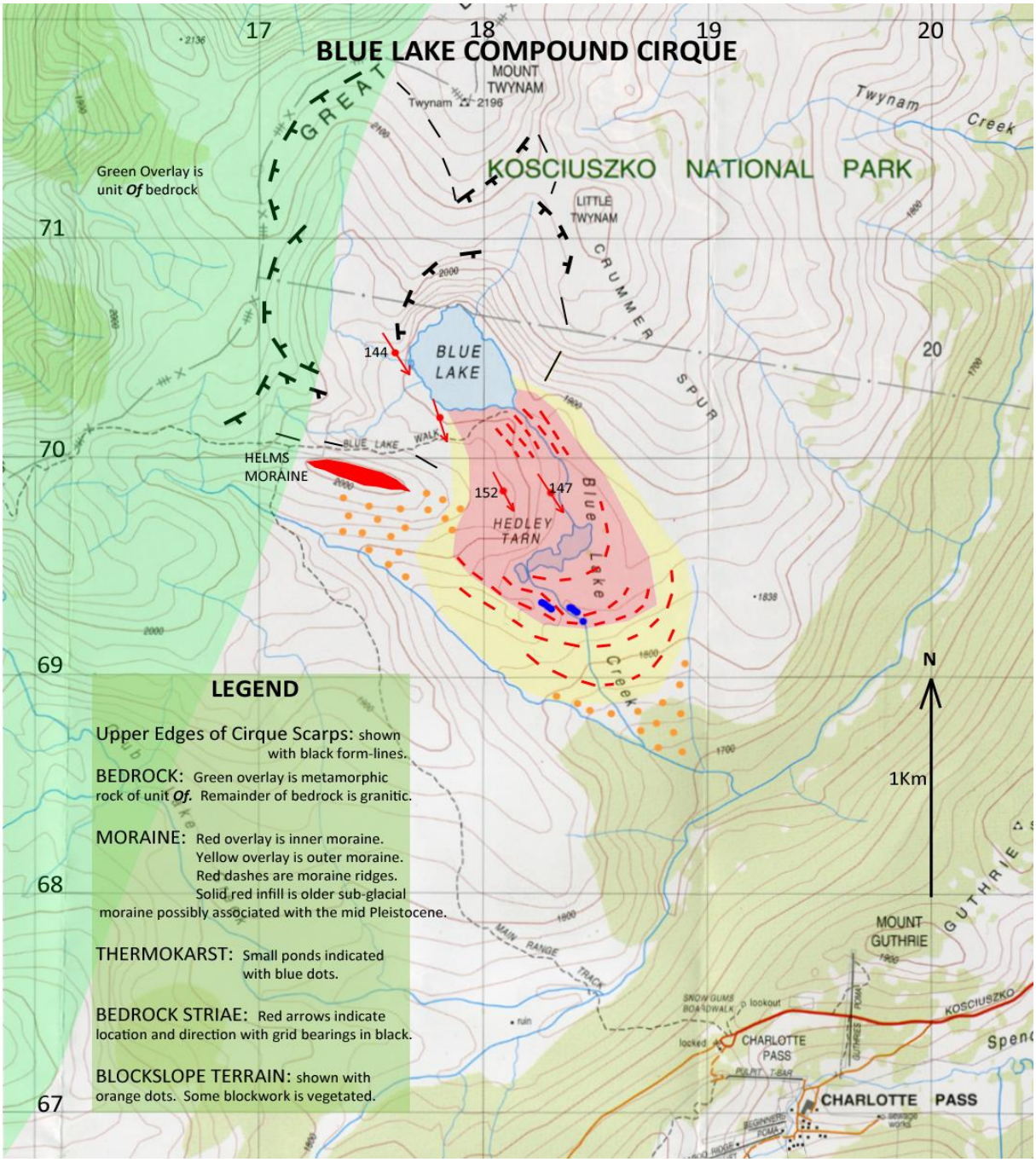


Figure 8.9: **Blue Lake Compound Cirque: glacial features**

A **green overlay** at 20% opacity delineates the metamorphic bedrock of unit ***Of***. Note that this metamorphic bedrock of unit *Of* lies west of Blue Lake and mostly above 2000m. **Red dashes** delineate ridges of moraine that stretch between Blue Lake and Hedley Tarn and also arcuate ridges within the inner and outer moraines. The ridges of moraine in the outer moraine are not well defined due to cryo-conditioning and downslope spreading. Glacial movement towards the SSE during the late Pleistocene is almost normal to the snow fences. **Orange dots** map open blockwork at the margins of the outer moraine and are indicative of cryo-conditioning of the outer moraine with frost-heave and gelifluction. Base map extracted from Perisher Valley 8525-2S Topographic Map © NSW Department of Lands, 2001.

Figure 8.10 **Distal portion of Blue Lake Outer Moraine.** Open imbricated blockwork in this outer moraine (BL-I), contrasts with the well-defined inner moraine in the following picture where the coarse component of the glacial debris is still embedded within its matrix. The imbrication above is evident here as large tabular blocks of granitic rock lap onto blocks downslope of them like a field of fallen dominoes. This is not an original fabric of glacial moraines. It represents uplift and downslope movement by frost-heave and gelifluction respectively. Refer to the *Kosciuszko Photoglossary* for more explanation if necessary.

Figure 8.11 **Inner moraine at Hedley Tarn**. This most recent terminal moraine below Blue Lake, dams back the shallow Hedley Tarn. The outlet of Blue Lake is about 800m upstream. The ridges of the inner terminal moraine below Hedley Tarn are well defined and also associated with pits and pools of water interpreted as thermokarst. This view looks southeastwards from the blockslope below Helms Moraine, (shown on figure 8.9). Note that the inner moraine ridge terminates below the blockslope.

The largest of the Kosciuszko Moraines is associated with Mawson Cirque. It is shown on the Kosciuszko Glacial Debris Map (figure 8.1) and also on the Map: Mawson Compound Cirque (figure 8.12), below. The Mawson Compound Cirque Map resulted from detailed mapping with the assistance of a colleague, Martin Fussell. Mawson Cirque also comprises inner and outer sets of recessional moraines as depicted in figure 8.12.

The younger, inner set is comprised of at least four moraine ridges as depicted in figure 8.13 below. Like the other *Kosciuszko Moraines,* the innermost portions of the inner moraines at Mawson Cirque have large circular depressions which are interpreted as thermokarst, and illustrated in figures 8.14 and 8.15. The output of the compound cirque comprising Mawson Cirque and Club Lake Cirque and the small cirque east of Mt Clarke appears to have decoupled during the last stage of the late Pleistocene glaciation, because Mawson Creek cirque and Club Lake cirque have separate sets of thermokarst pits as mapped in figure 8.12 (and illustrated in figures 8.14 and 8.15) and the small cirque east of Mt Clarke appears to have been non-glaciated during the last stage of late Pleistocene glaciation. The floor of the small cirque east of Mt Clarke has a vegetated blockfield which appears to be residual cryo-conditioned debris associated with the outer moraine of the Mawson compound cirque. **This further illustrates the increase in aridity throughout the late Pleistocene which minimised the accumulation of glacial ice but assisted the development of permafrost.**

The remaining examples of the late Pleistocene Kosciuszko Moraines occur at Wilkinson Valley and east of Mt Twynam. The latter have been outlined on figure 8.1 but the former have not been included on this map yet, as their distribution has not been resolved fully. The head of the Wilkinson Valley has a tiny moraine and a reentrant tucked into the 2100m contour at the foot of the summit rocks of Mt Townsend. The floor of this valley side is almost planar as it descends southwards from Mt Townsend, but the overall valley which descends from the col at GR 126680 in the Abbott Ridge, has the appearance of a glaciated valley for several kilometres downstream. This suggests that very little glaciation occurred here during the late Pleistocene but an earlier valley glaciation may have occurred here.

In concluding this topic on the *Kosciuszko Moraines,* it is evident that there are two sets of moraines coupled to the relict cirques of the Kosciuszko Main Range. The characteristics of these inner and outer moraines confirms their relative ages as deduced by Edgeworth David, 1908 and partially confirmed by cosmogenic radiometric dating by Barrows et al, 2001, who concluded that: ”***there is clear evidence of at least two main phases of glaciation on the Kosciuszko Massif, best represented by the inner and outer moraines at Blue Lake. There is no well preserved evidence of older or more extensive glacial events[74]”,……*** or is there?

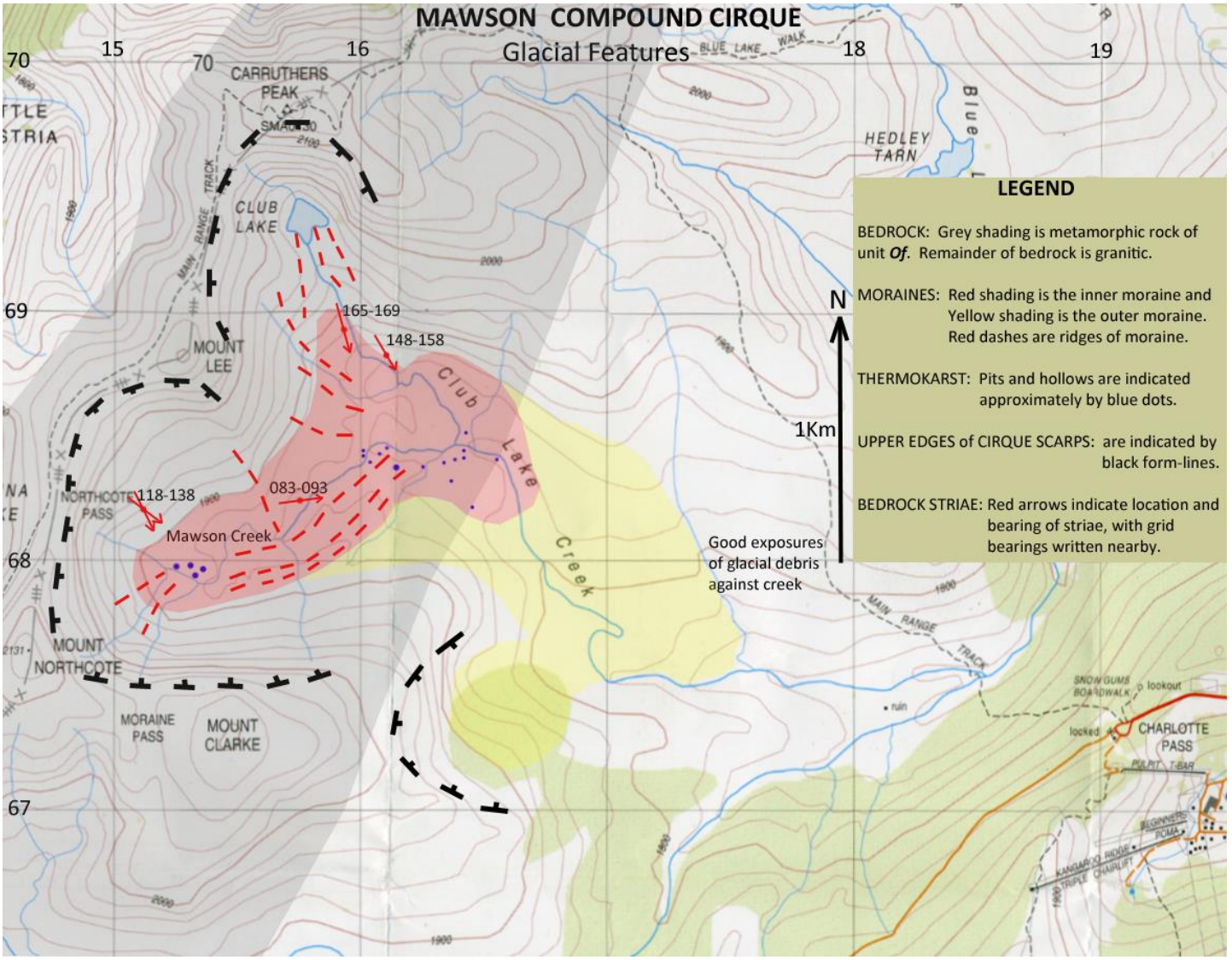


Figure 8.12. **Mawson Compound Cirque**. This map has been based on direct fieldwork with supplementation from land based photographs and satellite imagery.
The basemap was extracted from PERISHER VALLEY 8525-2S, Dept of Lands, NSW Govt., 2001.

Figure 8.13. **View from the backwall of Mawson Cirque looking ESE towards Charlotte Pass.**

Note the near parallel ridges of hummocky moraine that make up this inner moraine. Also note the pools of water within the innermost hummocky moraine suggesting thermokarst. Ridge 1 and 2 have subdued relief and are more discontinuous than ridges 3-6. Ridges 1 and 2 probably belong to the outer moraine. The main difference between these inner and outer moraines is the rounding and flattening of the outer moraines compared to the inner moraines. The Mawson Cirque is located within a metamorphic bedrock zone which produces a much smaller proportion of large blocky debris than granitic bedrock. As a result, the development of blockfield terrain as a result of frost heaving of large blocks within the outer moraines is very subdued here. It is also worth noting that striations in the bedrock of the backwall of Mawson Cirque, close to the viewpoint of this image, are aligned with a bearing of 130^{o}GB in the general direction of Charlotte Pass. A few pools within the innermost moraine of Ridge 6 are probably thermokarst. The next illustration is taken from the head of Mawson Creek to the right of this view.

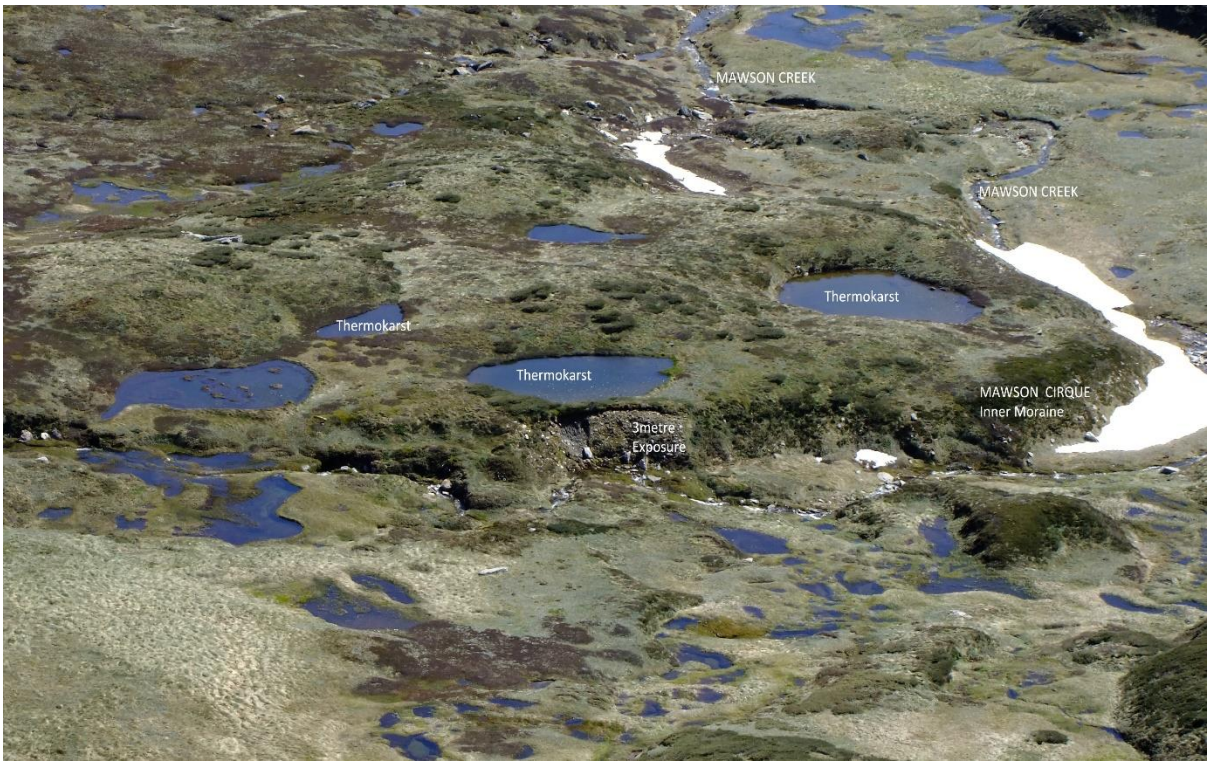


Figure 8.14 **View from the head of Mawson Creek** towards the northeast over the innermost moraine in Mawson Cirque. The moraine here has about 3 metres of relief and is peppered with circular depressions now filled with water. These depressions are interpreted as thermokarst and represent zones where ice bodies buried within the moraine have melted out and caused overlying material to collapse. The creek has also cut through the moraine in the valley floor, since the end of the ice-age and a fresh 3m exposed bank is visible against the middle thermokarst pit illustrated above. The creek bank exposure reveals glacial moraine comprising sub-rounded to sub-angular cobbles and blocks dispersed within a gravelly matrix.

Figure 8.15. **View towards Club Lake Cirque towards the northwest.** This hummocky moraine below Club Lake Cirque has a local relief of up to 10 metres above the valley floor. The large 5m deep conical pit in the foreground is probably thermokarst caused by the melt-out of ice within the original moraine below Club Lake Cirque. This inner moraine is well vegetated with a smattering of blocky debris at the surface like those at Cootapatamba, Albina and Rawson Creek.

End of Chapter 8 The Kosciuszko Moraines

Chapter Nine Tic Tic Toc Permafrost in my backyard?

This chapter develops the case for prior permafrost in the Highlands of southeastern Australia during the late Pleistocene. The **Tic Tic Toc** alludes to radiometric dating and the need to get on with this argument.

The development of active blockstreams in the northern hemisphere has a close association with active permafrost and the morphology of the relict blockstreams in Tasmania, Victoria and New South Wales is consistent with cryogenic processes such as frost shattering, frost heave, vertical sorting, frost creep and gelifluction.

The climatic conditions associated with prior permafrost in the Highlands of southeastern Australia are important to comprehend because they probably inhibited the development of glaciation in the Kosciuszko Region during the late Pleistocene.

As discussed in the previous chapter, the cosmogenic exposure dating of moraines at Kosciusko by Barrows et al in 2001 is as much evidence of prior permafrost as it is evidence of the age of the late Pleistocene moraines. **Permafrost** is a thermal condition of the ground which has caused it to become frozen solid for a significant period of time, possibly for thousands of years. A relatively thin uppermost layer usually thaws briefly on a seasonal basis and this is called the **active layer** in permafrost terrain. What supporting evidence do we have for prior permafrost at Kosciuszko or elsewhere in the highlands of southeastern Australia during the late Pleistocene Ice Age?

The highland terrain of the Bogong High Plains about 80km to the southwest of Kosciuszko contains no evidence of late Pleistocene glaciation but it does contain extensive accumulations of angular frost riven blocks in the form of *block glacii, blockstreams and blockslopes*. This region became the focus for an MSc research project,[75] unravelling what happened up here during the last Ice Age. The critical question regarding block accumulations is: *what characterises a pile of rocks as a **cryogenic** blockstream or blockslope?* (Cryogenic processes such as frost shattering and frost heave depend on very cold/dry conditions.)

It is my opinion that the evidence for prior cryo-conditioning in the development of now relict cryogenic blockfields, blockstreams and blockslopes is:

i. THERMOKARST; the surface morphology indicative of the melt-out of interstitial and sub-surface ice in the regolith (surface debris) which occurs after the climate warms up at the end of an ice-age.
ii. IMBRICATION OF BLOCKS: This describes the orientation of blocks, especially large tabular blocks, with blocks on the upslope side, overlapping blocks immediately downslope, like a sequence of fallen dominoes. This texture suggests plasticity and downslope movement which would be consistent with occasional seasonal thawing of the *active layer* in a permafrost environment, as well as slow permafrost creep on steep terrain.
iii. VERTICAL SORTING of clasts in the blockfield/blockslope profile with the coarse fraction towards the top and fines below, is indicative of repetitive frost-heave in the active layer within a permafrost environment.[76]
iv. CONTEXT: adjacent landforms that have a morphology consistent with cryo-conditioning, such as *cryoplanation terraces and nivation hollows.*
v. Supporting PALAEOCLIMATIC DATA from adjacent regions. (discussed in Ch. 10)

The above lines of geomorphic evidence are further described in the *Kosciuszko Photoglossary*.

With respect to **thermokarst**, I can find no systematic exploration of the resulting morphology of thermokarst within blockfields, blockstreams or block glacii in the literature which describes all those features caused by the melt-out of interstitial ice and sub surface ice within blocky debris. However, from my observations in the southeastern Australian Highlands there seems to be three forms of thermokarst associated with relict blockfields, blockstreams and block glacii:

i) *Broad deflation* of a blockstream; results in a concave cross-section with the centre line of the blockstream depressed by about 2 metres or more with respect to the edges which are sitting proud by about 0.5m with respect to the outside adjacent slopes. Refer to figure 9.1.

ii) *Thermokarst pits*: comprising small populations of conical to broadly curved depressions in the blockwork surface which may vary from 0.5m to 1.5m deep and usually 2m to 5m across. The size seems linked to the size of the blocks and the overall thickness of the block deposits. These pits often occur in clusters associated with reductions in gradient of the block deposit or on gently inclined steps and behind terminal blockstream ramparts. I think that these pits may have been the loci of small ice lenses at the base of the block deposits, possibly caused by freezing of groundwater when the blockstreams were active. Refer to figures 9.2a and 9.2b. The vegetated depression in the blockwork near Carr Villa (Ben Lomond, Tasmania) is about 10m across and at least 3m deep whereas the conical depressions at Basalt Hill are only 1.5m-2.0m across and less than a metre deep.

iii) *Furrows* in massive block accumulations are several metres deep and run downslope, often in a dendritic pattern for tens to hundreds of metres. They seem to be associated with pre-existing drainage lines and they have been observed in blockslopes on the Toolong Range and Happy Jacks area, south east of Cabramurra in the Kosciuszko National Park and also to the southeast of Mt Hotham, Victoria as well as the blockstreams on Mt Barrow, Tasmania. These furrows seem to have been caused by the thaw of massive, linear ice lenses which accreted in prior drainage lines in the floor of the blockwork during prior cold phases of the late Pleistocene. The water may have been effluent groundwater which cooled rapidly due to the **thermal regime**[77] within the open blockwork above. Refer to figures 9.3a, b and c.

Imbrication of platy or tabular debris occurs commonly in the fluvial environment as stream-flow slows down and the coarsest fraction settles down on the stream bed in a stable position. The imbricated debris in a fluvial environment is mostly platy cobbles, and the maximum diameter rarely exceeds 200mm. Imbrication of multi ton blocks in elevated alpine blockfields, on gentle to moderate slope gradients are not the product of fluvial action, as their surrounding terrain lacks the potential to develop the volume and velocity of water flow needed to get them moving. Most cryogenic block accumulations are in elevated terrain close to ridge-tops and summits with relatively small catchments above their location. Small, episodic movements of the *active layer* in a *permafrost zone* can be triggered by infiltration of snow meltwater and or thawing of the *active layer*. Water which is trapped above the permafrost table creates supersaturated debris which can slide down-slope on very gentle gradients, especially if the lower reaches of the active layer are fine grained.[78] Such occasional plasticity and instability will allow large platy blocks to slide until they meet some resistance and stack up against each other with an imbricate fabric. Refer to figures 9.4a and b.

Vertical sorting of particles from silt/sand size to boulder size occurs in permafrost environments with the coarsest blocks pushed towards the top of the profile and the finest sizes settling towards the base of the profile. This rearrangement of particles within the regolith profile is ubiquitous in a permafrost environment with blocky debris and is fairly endemic to the permafrost zone. This *vertical sorting* characterises the *active layer* in the *permafrost zone.*[79] Vertical sorting in blockfields/blockstreams has been reported by Caine and Jennings at the Toolong Range,[80] north of Kosciuszko and by Caine at Mt Barrow and Ben Lomond in Northeastern Tasmania,[81] which is illustrated in figure 9.5. Vertical sorting in a block glacis has also been observed by this writer at Basalt Hill in the Bogong High Plains.[82]

Context includes the association of landforms such as *cryoplanation terraces, nivation hollows* and occasionally *relict rock glaciers* (as at Mt Field, Ben Lomond and Mt Barrow, Tasmania) with associated development of blockstreams, blockfields and blockslopes, that make sense in terms of prevailing wind, bedrock structure and physiography. A *cryoplanation terrace* is a landform consisting of a terrace and small riser cut into bedrock by frost action, often forming a series of steps starting on summit flats and cascading down the lee side with respect to the prevailing wind direction. If the bedrock is well jointed like basalt, dolerite or granodiorite, then debris excavated from these cryoplanation terraces will comprise mostly coarse blocks which when transported downslope, will accumulate as block glacii, blockslopes and blockstreams further downslope. The prevailing wind controls the distribution of snow in the lee of the elevated terrain, especially under relatively arid conditions. The resulting thaw-water supports ice segregation and frost-cracking within the bedrock[83]. These block accumulations are well documented in the northern hemisphere where Washburn has demonstrated a close association with permafrost.[84] Figures 9.6 and 9.7 illustrate cryoplanation terrain at Basalt Hill on the Bogong High Plains, with terraces inset into the summit bedrock and cascading down the southeast slopes of Basalt Hill in the lee of the prevailing wind.

Supporting palaeoclimatic data

This includes inferences from regional studies in south-eastern Australia which indicate increased cooling and aridity during the late Pleistocene. These examples are discussed in some detail in chapter 10.

Now consider the blockstreams at Basalt Hill on the Bogong High Plains,[85] which are similar to blockstreams reported by Caine and Jennings, north of Kosciuszko. The terrain on the southeast flank of Basalt Hill is illustrated in figure 9.7. This small 40m thick plateau of basalt has a bedrock surface etched by terraces which cascade towards the southeast, which have fed the blockstreams. These basalt blockstreams form discontinuous threads, which terminate in convex ramparts whenever bedrock gradient is suddenly reduced by regular steps in the blockslope terrain. These basalt blockstreams extend 700m downslope beyond the edge of the basalt bedrock. The morphology of these blockstreams includes concave cross-sections and raised edges except near terminations where the blockstream has slowed and thickened to form a rampart on steps in the bedrock where the gradient has reduced down to 20-30% from steep back-slopes, with gradients of 50-60%. The raised edges give the impression that the whole blockstream has deflated with the greatest reduction in volume along the centre line of the blockstream.

There are also conical pits from 500mm-1000mm deep and up to 2m in diameter scattered over the surface of the blockstreams, but mainly concentrated where the gradient is less than 30%. These conical pits are collapse structures caused by the removal of some form of matrix between the blocks. These pits and the deflated cross-sectional structure suggest that there has been significant withdrawal of material from the blockstream since its emplacement, during the last cold phase of the Pleistocene. If silt, sand and gravel had formed the matrix between the blocks then the deposit would have behaved like a moraine and the residual blockstream would still retain much of the original matrix.

Since most relict blockstreams comprise open and relatively unweathered blockwork down to about 1m below the surface, the only material that could escape almost without trace is interstitial ice. A wet, mineral matrix would also have accelerated chemical weathering of the adjacent blocks, and this appears not to have happened.[86] Therefore, it is probable that these conical pits are thermokarst pits and the missing material was ice. Now compare this to Caine and Jennings description of the blockstreams on the Toolong Range, in the Kosciuszko National Park.

Toolong Range Blockstreams.[87]

Morphology

Slopes: 4.5-12^{o}
Length: 150-300m
Max Width: 70m
No free faces of bedrock at heads
Generally rectilinear profile
Concave cross profile
Edges: slightly higher than neighboring ground
Inclined steps /berms in long profile
Hollows:1m deep, pits their surfaces/ no regularity
Longitudinal V shaped groove in upper part of blockstream2, (2m deep).
Distal ends are generally convex in cross section and have a steep bulging toe, which may be 2m higher than surrounding terrain. Just above the toes, a level or slightly hollowed area occurs in which pitting is more common.

Stratigraphy

Sections dug into blockstream 1 (due to small block size). Structure conforms to 3 layered model established by Nel Caine for NE Tasmanian Blockfields. There are 3 Principal Layers:

Layer 1: Consists of matrix free blocks which decrease in size with depth.
Thickness: 100cm-150cm

Layer 2: Blocks with interstices filled by black humic material
Watertable occurs here.
Thickness: 20cm to 40cm for BS 1 , but as deep as 60cm near toe of BS 3.

Layer 3: Blocks with interstices filled by dark brown silty sand.
Thickness about 50cm in BS 1

At BS 1, these layers overlie a residual granite grus (extremely weathered granite) which retains original bedrock structure and demonstrates that unweathered basalt blocks have migrated downslope over extremely weathered granite bedrock.
This demonstrates that the basalt blocks have moved well beyond their original bedrock positions on gentle gradients and over catchments too small to provide traction of blocks by running water. What processes might have mobilised this blocky material?

There is a strong correlation between the block deposits at Ravine (Kosciuszko National Park) and Mt Little Higginbotham (Northeastern Victoria and just west of the Bogong High Plains), based on exposure dating and fieldwork by Barrows et al (2004) and also by observation of weathering rinds.[88]

Together with their geological context as elevated basalt cappings and their general proximity on the Great Dividing Range, there is strong similarity in block structure and degree of weathering of the blocks sampled by Barrows et al with the blocks at Basalt Hill, which suggests that the block glacis and the main blockstream at Basalt Hill were also probably formed during 16ka-23ka. Until exposure dating of blocks at Basalt Hill is undertaken, it is reasonable to extrapolate that the block glacii and adjacent basalt blockstreams at Basalt Hill were also probably active between 16ka and 23ka. Now consider some complementary evidence that supports the conditions necessary for Permafrost.

A survey of the upper Mitta Mitta and Kiewa Valleys revealed extensive deposits of sediments representing *stream-flood, sheet-flood and debris-flow facies* characteristic of alluvial fans, adjacent to the Bogong High Plains.[89] The distal alluvial fan deposits are now truncated by the modern river flood plain and lie beneath modern soil which indicates their relict status. They are poorly sorted sediment containing angular to sub-rounded clasts in fan-like deposits, but some of them form fan mesas, on elevated flattened spurs which indicates some further antiquity. These deposits have settled at the change in slope when a moving slurry of angular boulders, cobbles, gravel and mud have slowed down with the reduction in grade at the valley floor.

Alluvial fan deposits are characteristic of semi-arid landscapes with high relief and generally indicate a mean annual precipitation (MAP) of 250mm-500mm, but for those fans with a *mudflow/debris flow* component reaching 50% of an alluvial fan, the MAP is in the range 130-380mm.[90] The upper valleys adjacent to the Bogong High Plains currently have an annual precipitation in excess of 1000mm which suggests that precipitation during the late Pleistocene was conservatively less than 50% of current precipitation.

These alluvial fan deposits sit just below the change in slope near the 300m contour in catchments which rise steeply to 1000m or more. The Mt Beauty-Falls Creek road reveals many sections through steeply sloping gully fills made up of angular weathered blocks dispersed in a red clayey, silty, sandy, gravel matrix. These gully fills represent the individual feeders on steep elevated slopes, above the alluvial fan deposits.

From a stratigraphic perspective, these alluvial fan deposits and gully fills correlate with the cryogenic deposits, especially the weakly stratified cobbles of layer 2, in the *gelifluction* deposits marginal to the block glacii at Basalt Hill; which are also overlain by recent soil (layer 1). *Gelifluction* deposits are thin, surficial layers of cobbles in a matrix of gravel, sand and silt which have moved very slowly downslope over frozen, impermeable permafrost due to periodic thawing of the surficial *active layer*.

The relict alluvial fan deposits are indicative of a time when precipitation was probably less than 50% of present precipitation. These deposits are pre-Holocene and some are logically equivalent to the basalt

blockstream and glacii at Basalt Hill and elsewhere in the south-eastern Highlands of Australia, which in turn have been tentatively correlated as 16ka to 23ka or older. This correlation reinforces our comprehension of climatic conditions during cold phases of the late Pleistocene. Research on active blockstreams in the Northern Hemisphere indicate that they require a mean annual air temperature (MAAT) of less than minus 6 degrees Centigrade and an MAP of 100mm to 500mm.[91]

These conditions overlap with estimates of MAP associated with *alluvial fans* by Blissenbach, which have developed in the terrain below the blockstreams, throughout the highland terrain of southeastern Australia, which strengthens the correlation between cryogenic blockwork and the adjacent relict alluvial fans.

Finally, consider the following example of a blockstream on the flanks of the Farm Ridge, north of Mt Jagungal in the Kosciuszko National Park which is illustrated in figure 9.8. In this example the blockstream starts at the foot of an irregular scarp of basalt, 12 to 14m thick overlying Ordovician bedrock at 1545m altitude at the edge of a dissected plateau and descends to 1429m over a distance of 400m. The tributary gully it has accumulated in, drains towards the southeast in the lee of the prevailing wind.

The average gradient of this blockstream is 30% but the gradient decreases downslope. Longitudinal furrows or grooves are evident on the upper half, and the lower or distal end appears to have a bulging toe comprising several transverse lobes. The distal end of this blockstream has reached the floor of the main valley and has displaced the drainage line of the main valley (at right angles to the blockstream) about 20m towards the southeast.

The distal portion of this blockstream is very interesting in that it appears to have also changed direction and moved down the main valley floor (on 8% slope), at right angles to its dominant direction. Transport of coarse blockwork and redeposition as part of a discrete blockstream by the agencies of running water or gravitational sliding, with such a small catchment and on a gradient far less than required for gravitational sliding, seem improbable. An alternative mode of transport for the above displacement would be slow *permafrost creep* and/or small seasonal failures due to thawing of the *active layer* in a *permafrost environment,* known as *gelifluction*.

This feature appears to be a blockstream but it has transverse lobes similar to *rock glaciers* which move by slow plastic deformation known as *permafrost creep*. Caine and Jennings concluded in 1968 that the Toolong Range blockstreams which occur nearby, are "*akin to rock glaciers*". However, I think their mode of movement is more like sliding of a thin unstable active layer over an icy substrate rather than permafrost creep typical of the more massive rock glaciers. Modern researchers regard *rock glaciers* as a form of creeping permafrost.[92] The above relict blockstream on the Farm Ridge may not be massive enough to behave as a rock glacier but it shares similar features and has strong ties to permafrost.

Recent research into rock glaciers in the Swiss Alps which are deflating and melting due to a currently warming climate, reveal some interesting observations which may explain the low angle displacement

along 8% grade, of the distal end of the above basalt blockstream, descending from Farm Ridge in the Kosciuszko National Park. Ikeda et al (2003), investigated a small talus derived rockglacier in the eastern Swiss Alps with ice saturated sediments (permafrost) close to 0^{o}C within 5m of the ground surface. This ice-saturated debris showed rapid movement at 50-150cm per year accelerating over a 3 year period in response to rising temperatures.[93] In 2004 Lambiel and Delaloye published a study of creeping mountain permafrost in rockglaciers in the Verbier area of the Swiss Alps between 2000-2003.[94] They measured real time movement with GPS and observed vertical and horizontal displacements in the rockglacier surfaces. They concluded that warming of permafrost leads to acceleration of vertical and horizontal displacements as these rockglaciers decay in a currently warming climate.

This acceleration in movement of permafrost debris due to a warming climate may explain the final push over an 8% grade, of the blocky basaltic debris in the Farm Ridge blockstream (at the end of the last cold phase) discussed above and illustrated in figure 9.8 below.

In conclusion, I have presented an array of evidence which suggests that these blockslopes and blockstreams scattered throughout the highlands of southeastern Australia, were associated with permafrost conditions. The Kosciuszko National Park which covers 6,900km² has about 5000km² of terrain above 1400m altitude which means that most of that 5000km² of this elevated terrain would have been susceptible to cryo-conditioning, with the development of cryogenic block deposits, in discontinuous patches of permafrost, dependent on aspect and rock structure/rock-type.

Figure 9.1 **Blockstream southeast and below Basalt Hill, Bogong National Park, Victoria.**
This view upslope, illustrates a concave cross-section which may have been caused after interstitial ice and or ice lenses at the base of the blockstream melted at the end of the last cold phase. Another feature of these blockstreams at Basalt Hill is the mixed provenance of blocks. Most of the blocks are basalt derived from prismatic columns which have broken up into sub-angular fragments which are smaller than the larger, more rounded blocks of granodiorite. These basalt blocks have moved several hundred metres downslope from the closest basalt bedrock which caps Basalt Hill. The underlying bedrock here is granodiorite and there is a higher frequency of granodiorite blocks towards the edges of this blockstream. The five largest blocks in the foreground are all granodiorite, but how did they get here?

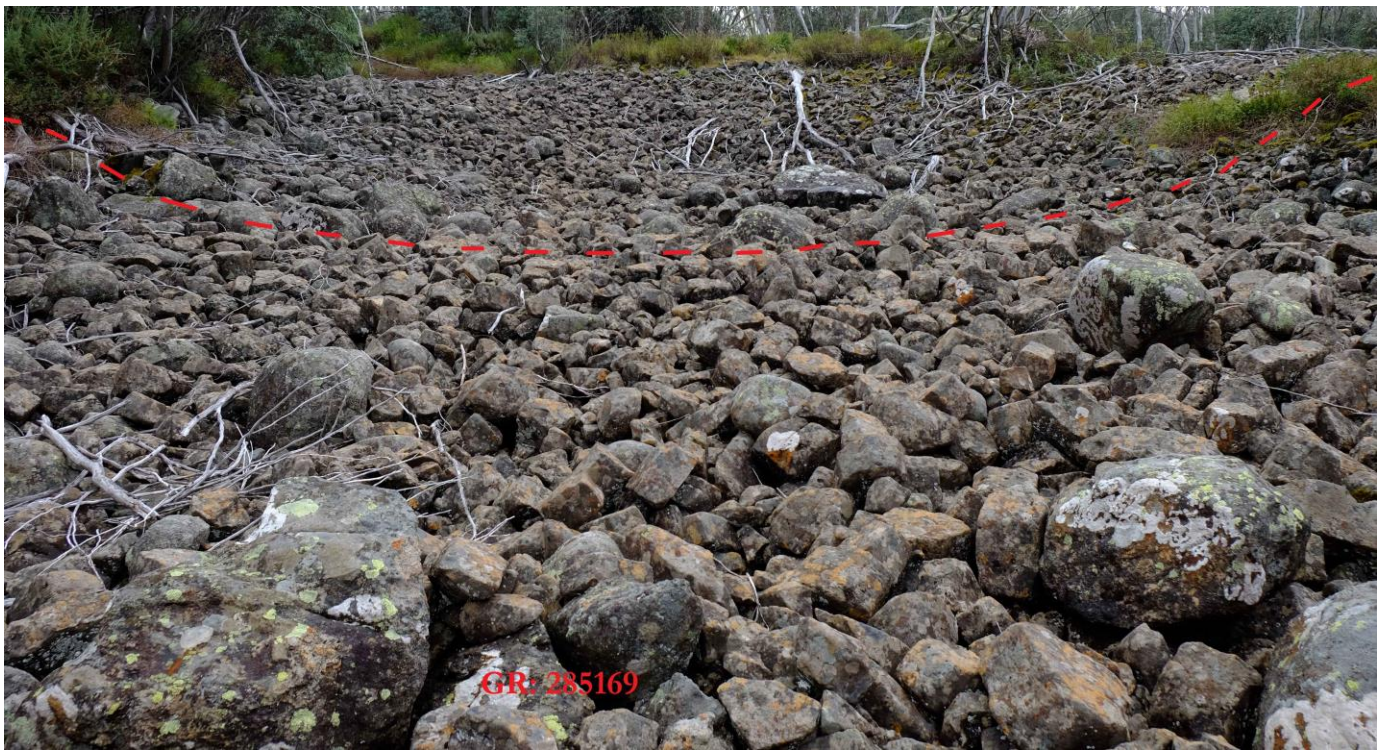


Figure 9.2a **Small thermokarst pits in small blockstream at the SE escarpment of Basalt Hill.**

Figure 9.2b **Large hollow in distal edge of relict blockslope, Ben Lomond, Tasmania**.

Figure 9.3a **Basalt blockslope and blockstreams** descending westwards from basalt capping on Boltons Hill down towards the Tumut River, Kosciuszko National Park. Note the dendritic furrows marked by shadows in the compound blockstream and also the blockslope. These furrows have probably been caused by the collapse of blockwork above ice accumulations in the prior drainage lines as the ice melted out at the end of the last cold phase of the late Pleistocene.

Satellite image downloaded from Google Earth on April 6th, 2020. ©2020 CNES/Airbus
©2020 Google

Figure 9.3b **Mt Barrow plateau, northeastern Tasmania**

This aerial photograph taken in early morning sunlight, shows up lightly vegetated ridges and shadowed furrows in the blockwork surface of the North Blockstream on Mt Barrow. The width of this blockstream at base of image is about 180m. The furrows were first reported by Nel Caine (1968) and they are up to 3m deep and run for hundreds of metres. These dendritic furrows are sympathetic to both the prior flow pattern of the open blockwork established by Nel Caine and also to prior water drainage. Since there is between 1 and 3 metres depth of open blockwork made up of sub-angular to sub-rounded blocks of dolerite, mostly less than 1m max dimension, on this North Blockstream, it is unlikely that surface water had any role in the development of these surface grooves. They have probably resulted from the meltout of ice beneath the blockstream. Such ice would have accumulated in the prior drainage lines as thaw water or ground water which passed beneath the accumulating blocks. The thermal regime of open blockwork can suppress air temperature within the blockwork and accelerate freezing and the development of **permafrost**. Nel Caine stated in his conclusion that "*no cryokarstic features have been found in either the blockfields or the vegetated blockfields"*‡ [at Ben Lomond or Mt Barrow], but he reported features at Ben Lomond and Mt Barrow, in northeastern Tasmania which have also been observed in blockstreams on the Bogong High Plains and the Toolong Range north of Kosciuszko. These features include: concave cross-sections; sets ot pits or depressions in the blockstream surface and longitudinal furrows in the blockstream surface. These features are probably ***thermokarst*** and are indeed indicative of prior ***permafrost***.

‡refer to end-note 82 of chapter 9 and in particular, p110 and 19-32 of this reference.

The archived image below was downloaded from Google Earth on 25/5/2020. Image © 2017 Digital Globe.

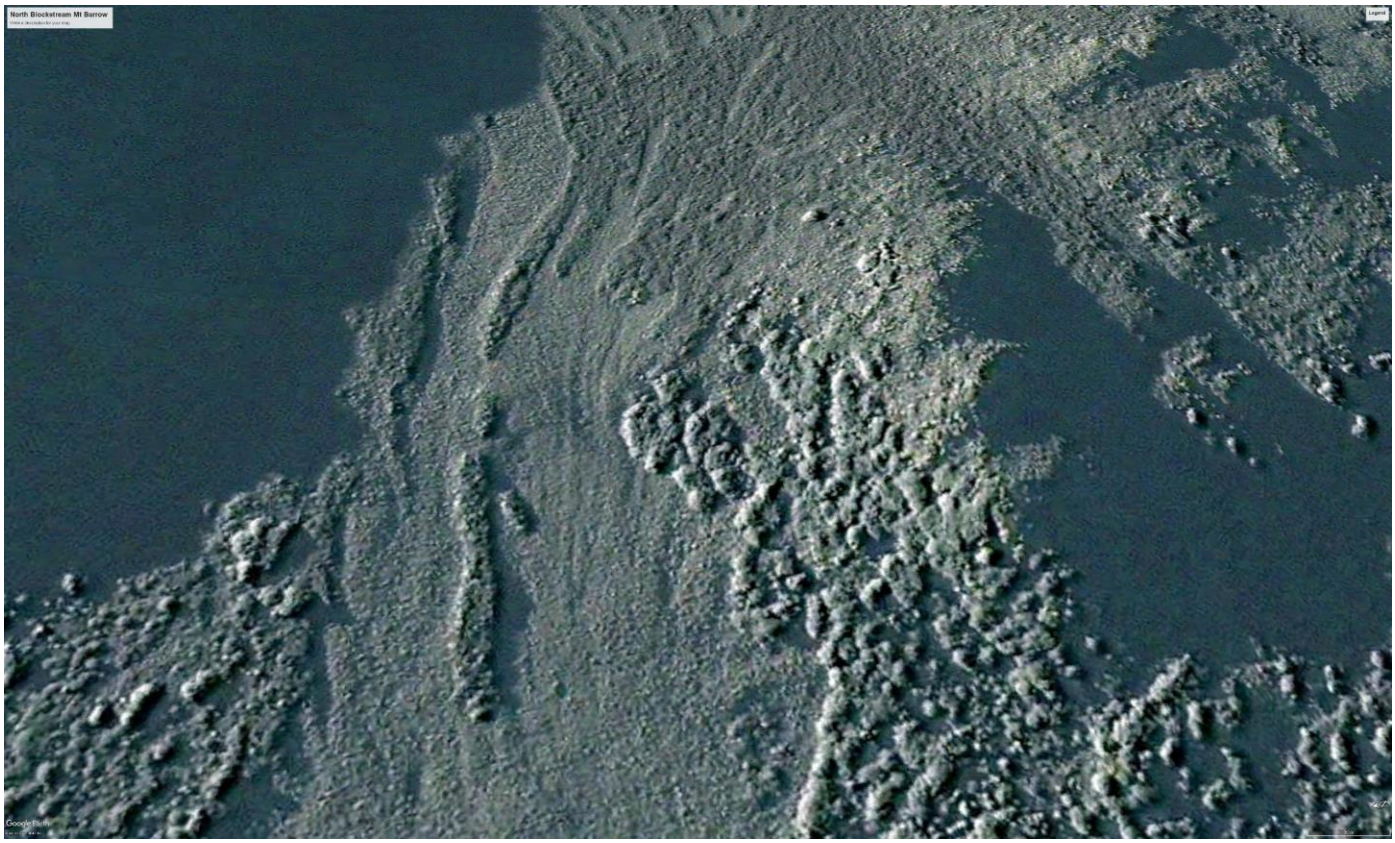


Figure 9.3 c **Blockslope and blockstreams (to the left) on the western flank of the Farm Ridge, Kosciuszko National Park.**

This steep blockslope between 1540m and 1435m is made up of basalt blocks derived from a thin basalt lava capping less than 20m thick on the top of the Farm Ridge. The blocks have migrated down the flanks of the Farm Ridge but are now immobile. This blockslope is interesting because of the dendritic furrows marked by shadow-lines cast by the afternoon sunlight. These furrows are similar to those furrows first reported by Nel Caine on Mt Barrow, Tasmania in 1968. The dendritic pattern is sympathetic to surface drainage and probably reflects surface drainage prior to the migration of blocks which created this blockslope. The furrows can be explained as collapse features after the melt-out of ice which accumulated beneath these blocks and within the prior drainage lines. It has been established that open blockwork develops a thermal regime which depresses the air and ground temperature beneath open blockwork. Such a thermal regime would accelerate the development of permafrost which in turn would promote downslope movement of the blocks, during seasonal thaw events, by *gelifluction*.

Satellite image downloaded from Google Earth on 4/4/2020. Image © 2020 CNES/Airbus

Figure 9.4 a **Small granodiorite blockstream near the aqueduct at 1610m asl, and south of Basalt Hill, Bogong High Plains, Victoria**.

These large, tabular granodiorite blocks have migrated south and downslope on a gentle gradient of less than 10%. They are 100m downslope from the closest granodiorite bedrock, upslope. As they came to rest in this minor drainage line, these big blocks stacked up against each other like fallen dominoes. This is a common feature with large platey or tabular blocks in relict cryogenic blockstreams in the highlands of southeastern Australia. This stacked arrangement with upslope blocks lapping onto downslope blocks is called an ***imbricate*** arrangement or fabric. These blocks have probably been transported by ***gelifluction*** which is a slow, spasmodic mechanism whereby the uppermost layer of permafrost becomes unstable due to seasonal thawing. The thaw water cannot escape into the frozen permafrost below which causes the uppermost, thawed layer to become supersaturated and unstable, even on gentle slopes. These processes appear to be inactive in the present climate.

Figure 9.4 b **Imbricated dolerite blocks at distal edge of blockslope on northern slope of Ben Lomond, Tasmania.** The blocks in the foreground are viewed side-on and they are stacked with an imbricate pattern. This arrangement of the blocks is not random, it represents a common depositional pattern for platy blocks that have been transported in a fluid medium. It is a common texture within platy cobbles deposited by running water. These blocks are angular and have not been abraded and smoothed by the rapid motions of running water. The mechanism that moved these blocks the 300 odd metres from the cliff base above, took about 500,000years. This timing has been established by cosmogenic exposure dating (by Barrows et al, 2004)‡ for a sequence of blocks between the upper edge of this blockslope and the lower, distal margin in the foreground. This represents a fairly slow ride downslope. ***Intermittent creeping permafrost*** and/or ***gelifluction*** are the most likely culprits and these processes may have been active here for several thousands of years during each successive cold phase within the set of 100,000yr climate-cycles during the late Pleistocene.

‡ Timothy T. Barrows, John O. Stone, L. Keith Fifield, "Exposure ages for Pleistocene periglacial deposits in Australia", *Quaternary Science Reviews*, **23**:697-708, (2004).

Figure 9.5 **Road cutting near the base of the blockslope on northern approach to Mt Barrow.**

This 2-3m section through the lower portion of this dolerite blockslope on the northern flanks of Mt Barrow displays sorting within the blockslope. The coarsest blocks are towards the top and smaller blocks are towards the base of this section. This blocky layer is portion of the prior *active layer*. It probably descends further down to cobbles within an orange-brown sandy/clay layer below. This vertical sorting can be achieved by *frost-heave* in a *permafrost environment*. Observations and experiments by Arturo Corte (1966)‡ have demonstrated that seasonal freeze-thaw in a permafrost environment will sort surficial debris with largest blocks heaved towards the surface and fine debris filtering downwards in the profile. Comments by Nel Caine in relation to sections observed at Ben Lomond and Mt Barrow (1968)† and Caine and Jennings (1968)§ in relation to pits dug within the Toolong Range blockstreams, note that these sections appear to be *vertically sorted*. This writer has also observed vertical sorting within a basalt block glacis near the southeastern flanks of Basalt Hill†‡. *These relict examples of vertical sorting within blocky debris, suggest that permafrost has been active in the past*.

‡ end-note 79; † end-note 81; § end-note 80; † ‡ end-note 82 at end of book.

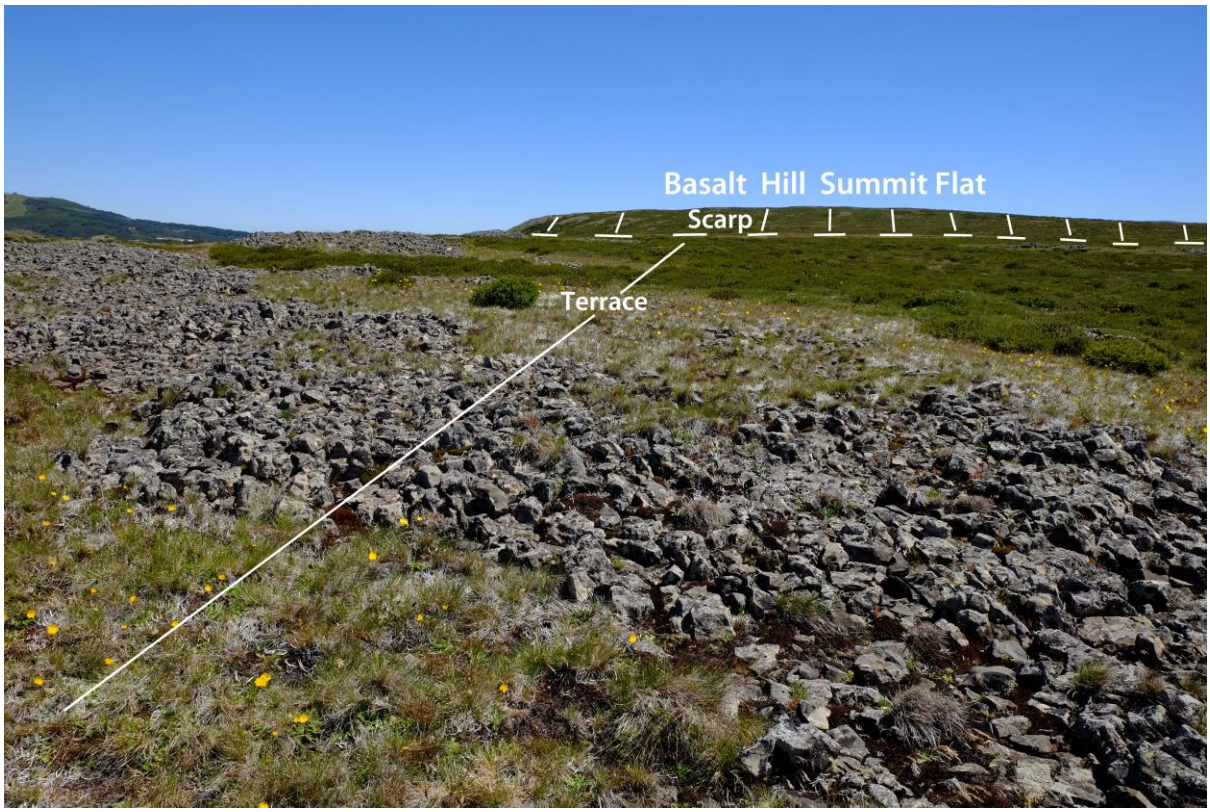


Figure 9.6a **Cryoplanation terrain, Basalt Hill, Bogong National Park, Victoria.**

These bedrock terraces at Basalt Hill, adjacent to the summit and sloping gently eastwards and southwards are relict features, as is evident by their partial burial beneath modern soil and vegetation. According to Washburn (1979), cryoplanation terraces have a veneer of blocky debris above bedrock and may develop patterned ground, indicative of permafrost. Cryoplanation produces summit flats or benches with a gradient of 2° or less. Distribution of cryoplanation terraces in Russia demonstrates a close association with active permafrost‡. Rock structure such as jointing may help influence the location and degree of development of some terraces but they seem to be developed on all rock types on the Bogong High Plains where the terrain is elevated and exposed and underlain by well-jointed bedrock. Coarse open blockwork however is restricted to rock-types with suitable jointing such as basalt, dolerite and some granodiorites on the Bogong High Plains.

‡Washburn A. L.,1979. *Geocryology: A survey of periglacial processes and environments.* London: Edward Arnold. pp237-240.

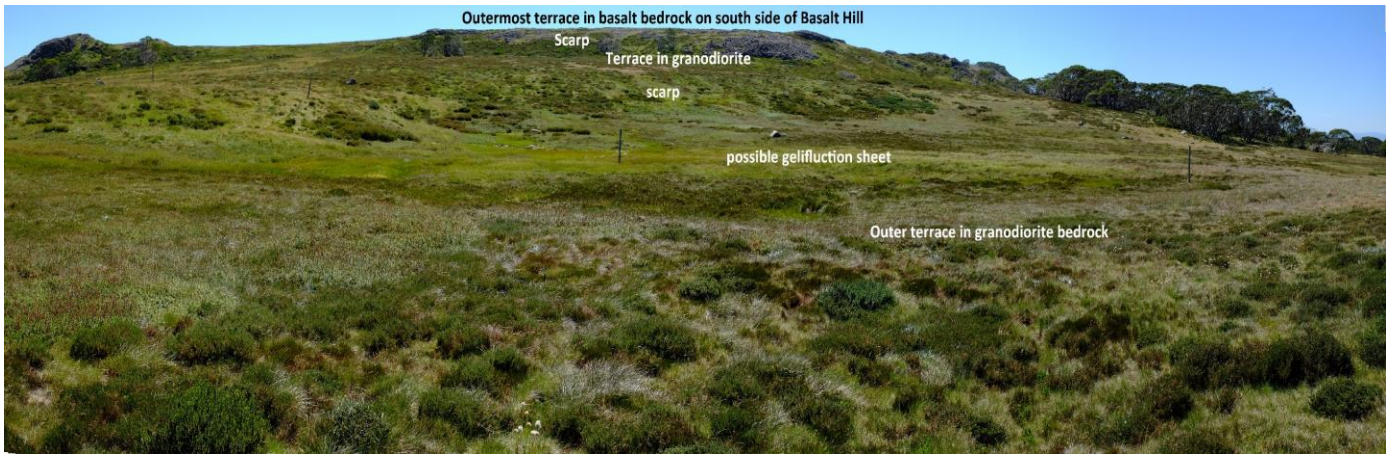

Outermost terrace in basalt bedrock on south side of Basalt Hill
Scarp
Terrace in granodiorite
scarp
possible gelifluction sheet
Outer terrace in granodiorite bedrock

Figure 9.6b **Terraces cut into bedrock beyond those shown in Figure 9.6a on the southern side of Basalt Hill** The two terraces and scarps starting in the foreground and looking back towards the outermost terrace in basalt bedrock on the south-side of Basalt Hill are a continuation of stepped terrain. This stepped terrain continues further downslope to the southeast underlying the blockslopes and blockstreams shown in the satellite image of Figure 9.7 below.

This stepped terrain with its veneer of angular blockwork to the southeast of Basalt Hill is consistent with the description of cryoplanation terrain described by A. L. Washburn (1979) and referred to above.

Also note the vegetated sheet of non-blocky debris in middle of view which is interpreted as a relict gelifluction flow/sheet.

Figure 9.7 **Basalt Hill Overview, Bogong National Park, Victoria.**

This view displays a large vegetated blockslope with open blockwork in the drainage lines to the southeast of Basalt Hill. Significant quantities of basalt blocks excavated from the capping above the level of the snow patches, visible above the aqueduct, have been transported downslope for up to a kilometre. Where the blocks have gravitated into drainage lines, they form blockstreams as a dendritic network of feeders, with some secondary movement down the streams themselves, despite insufficient gradient for free gravitational sliding. There are no bedrock cliffs feeding blocks onto the blockslopes by gravitational rolling.

The visible snow-patch zones mark the southeast edge of basalt bedrock, which comprises two separate lava flows with a cumulative maximum thickness of about 40 metres. Granodiorite bedrock occurs down-slope of the snow-patch zone in the vicinity of the blockstreams.

Surface features on these blockstreams/blockslopes give clues to their genesis. The blockstreams here show evidence of prior permafrost conditions which allowed the subsurface accumulation of ice, which melted out at the end of the late Pleistocene and created thermokarst pits and concave cross-sections. Transverse ripples and ramparts in the blockwork suggest longitudinal movement down the blockstreams consistent with *permafrost-creep or gelifluction*. Granodiorite bedrock has contributed to the blockwork at the edges of the basalt blockstreams and the proportion of granodiorite blocks also increases towards the NE, from the main basaltic blockstream above the 1400m spot height. There seems to have been two separate accumulation periods, with fresh looking basalt blockstreams over-riding older, very weathered granodiorite blockstreams in the lower reaches of the blockstreams at Basalt Hill. The bedrock at Basalt Hill has a stepped profile moving downslope, consistent with cryoplanation. The largest cryoplanation scarp is now occupied by residual snow in the satellite image below.

Satellite image downloaded from Google Earth on 26/1/2019. ©2018 CNES/Airbus. ©Spot Image

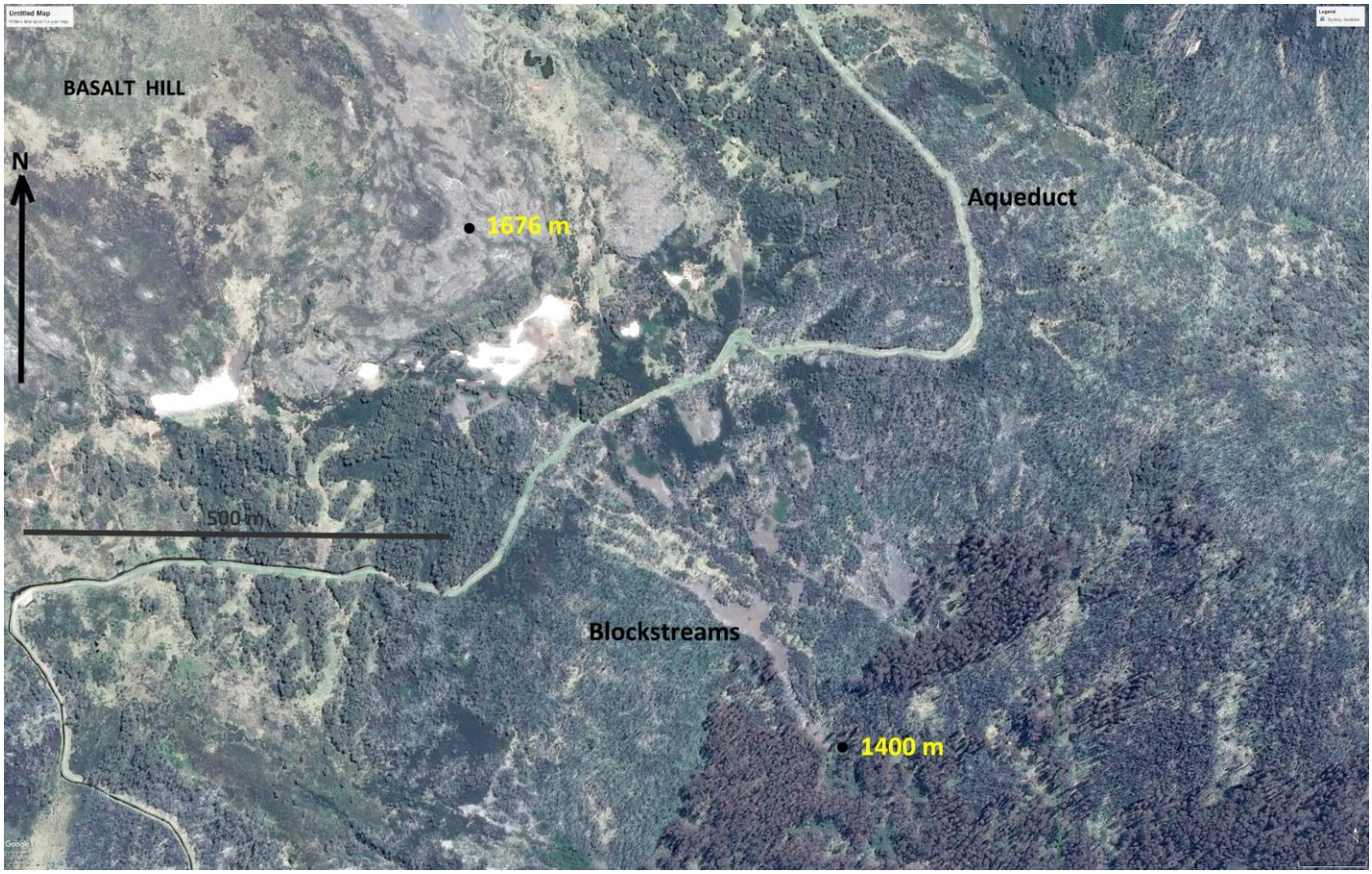


Figure 9.8 **Overview of the southeast escarpment of Farm Ridge in the Kosciuszko National Park**.
The elevated surface of the Farm Ridge appears in the upper left hand corner of view. In the example below, the 1st and longest blockstream starts at the foot of an irregular scarp of 12m to 14m thick basalt capping, overlying Ordovician metamorphic bedrock. It starts at 1550m altitude and descends to 1429m over a distance of 400m. This blockstream drains towards the southeast and the small valley at the foot of the blockstream joins the Tumut River to the southwest. The average gradient of the blockstream is 30% but decreases downslope. Longitudinal furrows are evident in the upper half of the 1st blockstream and along most of the middle blockstream. These furrows are similar to those reported by Caine in Tasmania and by Caine and Jennings 1968 for the Toolong blockstreams to the south of here. The lower or distal end of the 1st blockstream appears to have a bulging toe made up of several transverse lobes. The distal end of this blockstream has reached the floor of the valley and has displaced its drainage line, for about 20m towards the south east. This blockstream is very interesting because very few of these blockslopes/blockstreams reach the floor of their adjacent valleys, let alone displace the local drainage line. The far end of this blockstream is also unusual in that it appears to have changed direction and moved down the valley floor towards the south-west for about 60m on a gradient with 8% fall. **It is difficult to argue any mode of transport for this blockwork on such a gentle grade.**
Slow permafrost creep would be a viable mechanism on the steeper sections of this blockstream but is problematic at 8% grade. Rapid degradation of permafrost in rock glaciers of the Swiss Alps;{ Ikeda et al (2003) and Lambiel and Delaloye (2004) end-notes 93 & 94 }, has caused acceleration of permafrost creep from about 20cm/yr to 135cm/yr under a warming climate. *A rapid extension of this blockstream due to melting and deflation of the permafrost core may also have caused a strong terminal push at the distal end of the blockstream during the warming phase at end of the last cold phase of climate. Also, gelifluction of the active layer on a decaying permafrost core might provide the final displacement over very low gradients*. This basalt blockstream illustrates some of the typical cryogenic features which can be found across the basalt tablelands in the northern reaches of the Kosciuszko National Park. During the last cold phase of the Pleistocene, most of the 5000km² of elevated terrain above 1400m in the Kosciuszko National Park was not glaciated but was instead subjected to cold/dry conditions. Localised and discontinuous zones of permafrost developed where local conditions such as gradient and aspect affect insolation, like the SE aspect of the blockstream below. These local conditions as well as rock-type and the thermal regime associated with open blockwork, have optimised the development of permafrost in the example below during the late Pleistocene.
This satellite image was downloaded from Google Earth on 25/1/2019 and is ©2018 Digital Globe.

Given the broad distribution of relict blockstreams and blockslopes throughout the Kosciuszko National Park, in elevated terrain above 1000m, one can only conclude that sporadic mountain permafrost was widespread during 16ka to23ka and possibly during earlier cold phases of the late Pleistocene Ice Age. The sporadic character is probably controlled by aspect and scarcity of moisture in a cold arid environment. *Permafrost* has interacted with *susceptible rock* types like basalt, rhyodacite, granodiorite and dolerite to produce extensive deposits of *cryo-conditioned blockwork* in south-eastern Australia. *Glacial debris* comprising coarse blocks and boulders in a finer matrix was also susceptible to *cryo-conditioning* if not protected by a perennial blanket of snow. Permafrost conditions in the late Pleistocene would have been capable of frost-heaving of the blocks and boulders in pre-existing glacial debris, to create a blockfield on the surface of the original glacial deposits, which is what we see in all the outer/older Kosciuszko moraines.

In the Kosciuszko area there are extensive examples of blockslope/blockstream terrain; starting with the western flanks of Kosciuszko itself, illustrated in figure 9.9. On the windswept western slopes of Kosciuszko this open unvegetated blockstream on Rawson Pass Adamellite bedrock, spans 550m on a gradient of 22%. Much of the adjacent terrain is vegetated blockslope. However, the Mowamba Granodiorite is the most widespread rock type in this region and figures 9.10a, b and c, illustrate a relict blockslope and blockfield/block glacis near Charlotte Pass. On the steep southeastern slope below Charlotte Pass, a large blockslope terminates in a block glacis on the gently sloping valley floor of upper Spencers Creek and it exhibits imbricated blocks and large depressions 10-20m across and several metres deep. These depressions are marked by dense heath vegetation within the blockwork.

Further down Spencers Creek and below its junction with Betts Creek, the eastern flank of Spencers Creek displays a continuous vegetated blockslope with massive unvegetated blockstreams following minor drainage lines, down to the main creek with a distal edge about 3m thick, as shown in figure 9.11. Further, along Betts Creek on the south-western flanks of Mt Wheatley, well defined imbricated blockstreams emerge out of the vegetated blockslope as seen in figure 9.12, adjacent to the Kosciuszko road. Figure 9.13a in the catchment of upper Merrits Creek at the southern end of the Kangaroo Ridge, shows a broad blockfield on a western aspect in Mowamba Granodiorite, below the terraced bedrock ridgeline. Fig 9.13b looks cross-slope and reveals some imbrication, suggesting downslope movement. Finally, on the eastern flanks of the Kangaroo Ridge, a massive blockstream descends upper Wrights Creek (figure 9.14), towards a broad U-shaped incision hanging in the valley floor below.
The paragraphs above illustrate the widespread development of block debris on Granodiorite bedrock near to and just northeast of Kosciuszko. These block deposits have a signature which suggests a cryogenic genesis consistent with permafrost terrain.

These examples of relict blockslope/blockstream terrain in the KNP also correlate well with relict blockslope/blockstream terrain in: northeastern Victoria; and northeastern Tasmania, which are also associated with ***cryo-conditioning*** during the late Pleistocene.
Evidence from the northern Hemisphere strongly supports *the coexistence of blockstreams within permafrost terrain* which is discussed further in the next chapter on palaeoclimatic evidence, (Time-Out).

At Kosciuszko there is an additional consideration which supports *permafrost conditions during the last cold phase*. At Kosciuszko, glacial debris of the *inner moraines* deposited during the last glacial phase has been dated as 16ka-20ka at Blue Lake and Cootapatamba, and these inner moraines retain their original texture, whereas the older *outer moraine* appears to have been modified by cryo-conditioning during the late Pleistocene. Barrows et al have estimated the maximum age of the outer moraines at Blue Lake as 59,300 +/- 5400 years before present.[95] This estimate appears to be flawed, but before reading on, it would be useful to refer back to figure 8.9 (Glacial Features Map Blue Lake), in chapter 8, which shows the Outer Moraine below Blue Lake where the 3 samples from (BL-I) were collected close to the 1780m contour. Below this Outer Moraine is a further deposit marked as *Blockslope Debris* which is referred to by Barrows et al as the "*boulder field*", which was also sampled and is discussed below.[96]

If you compare the maximum cosmogenic exposure ages (above), to evidence of peak climatic cooling from the Vostok Ice Cores and also the Deep Sea Drilling Project data from site 595 which correlate at approx. 60ka to 70ka years before present,[97] you will realise that the outer moraine (BL-I) is older than 59,300 years before present. Both the above items of evidence of peak climatic cooling were presented by Barrows et al (2001) and despite the large spread in exposure ages for blocks sampled in (BL-I), they ignored the unreliability of a spread of 20,000 years across 3 samples and concluded that the single measurement of 59,300 yrs must represent the maximum age of this moraine, (BL-1). This is despite the realisation that "*boulders on the moraine flat* [BL-I] *may have been exhumed from beneath till since the moraine was deposited.*" The *boulder field* below the outermost moraine (BL-I) sampled by Barrows et al, "*gave a more coherent set of ages*" with a maximum exposure age of 61,700 years.[98] The above researchers have failed to realise that this "*boulder field*" probably represents a complete reworking and dispersal of the lower edge of the outer moraine (BL-I) by cryogenic processes and that this exposure age of 61,700 years, post-dates the original deposition of the outer moraine (BL-I). The most probable age for the deposition of the outer moraine (BL-I) is within the span 60ka-70ka and prior to 61.7ka.

Cryo-conditioning of old moraine is the only satisfactory explanation for the apparently inconsistent and anomalous exposure ages obtained by Barrows et al (2001) in the outer moraines below Blue Lake.

Cryo-conditioning was probably active during 61.7ka-59.3ka and 23ka-16ka and possibly during intermediate intervals as well.
These cosmogenic exposure ages have given consistent and reliable ages for the inner moraines but their greatest value is in demonstrating the probable presence of permafrost and cryo-conditioning at Kosciuszko during the late Pleistocene. The palaeoclimatic evidence supporting this point of view is considered in the next chapter: Time-Out.

Diagrams 9.9 to 9.13 follow with some discussion of each illustration.

Figure 9.9 **Massive vegetated blockslope of Rawson Pass Adamellite with open blockstreams on the western flank of the Kosciuszko Ridge.**

The longest open blockstream here runs for 550m with an average grade of 22%.
This entire western slope of the Kosciuszko Ridge is covered in blocks and it appears that permafrost with a low residual snow-pack was active here for most of the late Pleistocene. On the eastern side of the ridge is a small relict glacial cirque centred on Lake Cootapatamba. It is a marginal feature without significant undercutting of its base and it was probably active when the blockslopes on the opposite side of the ridge were also active. The Cootapatamba cirque-style glacier owes its existence to an efficient snow-fence in the form of the Kosciuszko South Ridge, whereas the western side of the ridge on the windward side of the prevailing winds would have collected relatively little snow during the late Pleistocene. A thin snow pack would not off-set seasonal freezing of the bedrock and regolith below the snow pack, whereas a thick snow pack would have inhibited the development of permafrost and cryo-conditioning. These blockslopes/blockstreams further reinforce the relative aridity of climate here during the late Pleistocene.

Satellite image downloaded from Google Earth on 2/2/2019. Image© 2019 CNES/Airbus

Figure 9.10a **<u>Upper Spencers Creek, near Charlotte Pass, Kosciuszko National Park</u>**

This view looks down from Mt Guthrie onto this blocky debris which has accumulated as a steep blockslope on the south-east flank of Charlotte Pass. The bedrock here is Mowamba granodiorite. The steep *blockslope* transitions to a gently sloping *block glacis* on the valley floor which thins out towards the distal edge.

This feature has similarities to the blockslope/block glacis at Pine Mountain on the northern edge of the central Plateau, Tasmania, illustrated in the *Kosciuszko Photoglossary*. It is highly probable that cryo-conditioning and permafrost were responsible for the Pine Lake block glacis and were also active here during the late Pleistocene due to imbrication of the blocks and possible thermokarst at both locations.

Figure 9.10b **View across distal edge of granodiorite blockslope in upper Spencers Creek.**

Large slabs of Mowamba granodiorite on a moderately steep slope transition to a very gentle slope at left of centre. Vegetated portions occur in depressions which may represent thermokarst. Charlotte Pass is located in the saddle on the ridge-line, at right of centre.
Imbrication of the large blocks of Mowamba granodiorite are well represented in this image. This rock fabric is indicative of flow. This whole blockslope flowed down-hill very slowly, probably under the influence of *permafrost creep and/or gelifluction*. The open structure of the blockwork here is typical of the *active layer* in zones of actively *creeping permafrost* in the European Alps. Current climatic conditions here are incapable of supporting permafrost and these blockslopes seem to be very stable including sections cut through them by the roadway above. One would expect exposure ages similar to those at Mt Little Higginbotham and perhaps as extensive as those recorded for the blockslope on Ben Lomond, (Barrows et al 2004), end-note 44b.

Figure 9.10c **Distal end of blockslope/block glacis at the head of Spencers Ck near Charlotte Pass, Kosciuszko National Park.**

The vegetated depressions in the left foreground and near centre of view are probably thermokarst. The low gradient of the apron of granodiorite blocks making up this block glacis is comparable to the Pine Lake block glacis in northern Tasmania, illustrated in the *Kosciuszko Photoglossary*, slide 32. The cluster of blocky debris in the lower right-hand corner may be the result of in situ weathering and breakup of a granodiorite block or portion of the block beneath. These blocks show significant exfoliation of their exposed surfaces, supporting their relict status.

Figure 9.11 **Mid-section, Spencers Creek, relict blockslope, Kosciuszko National Park.**

This west facing slope is continuous relict blockfield. Away from local drainage lines the blockfield thins and has become vegetated. Towards the drainage lines the imbricated blockwork thickens and remains open structured. The centre-line of the tributary drainage line (which runs from top-centre diagonally to the right) is depressed, which is a form of thermokarst. This blocky drainage line is a blockstream within the blockfield and it forms a blocky barrier where it merges with Spencers Ck to the right of image. There are several of these block terraces across Spencers Creek in this area which form large ponds. Blocks moving downslope have also stacked up in an imbricate manner along the edge of Spencers Ck which is evident at left of centre. These block barriers dam back Spencers Ck into a string of ponds which were originally interpreted by Edgeworth David in 1908 as glacially scoured ponds. This valley was probably glaciated during the early/mid Pleistocene but during the late Pleistocene it was affected by cryo-conditioning and these block features here at Spencers Ck are consistent with a permafrost thermal regime and prior creeping permafrost.

Figure 9.12 **Cutting on Kosciuszko Road southwest of Perisher Gap near old Betts Camp.**
These platy slabs of Mowamba granodiorite form an imbricated blockstream along a drainage line running up the centre of view. This drainage line is a tributary of Betts Creek which in turn flows westwards into Spencers Creek. The adjacent slope is vegetated blockslope, similar to that illustrated in figure 9.11 at Spencers Creek. In addition to an imbricated arrangement of the large surficial blocks, there also appears to be an indication of vertical sorting with finer material towards the base of the section. Both this blocky imbrication and the apparent vertical sorting are consistent with prior permafrost conditions. W. R. Browne (1956, p115)‡ considered that this blocky debris was moraine, caused by a 300m ice-sheet moving eastwards from the Main Range towards the valley of the Crackenback River. This blockslope does resemble the outermost, reworked moraine (BL-1) below Blue Lake. However, this writer has found no exotic/erratic blocks in this area which could have been transported from the metamorphic bedrock on the Main Range and therefore I do not consider that this area was over-run by an eastwards spreading ice-sheet. Ice from this catchment may have contributed ice moving westwards from Perisher towards the Spencers Creek valley during the early-mid Pleistocene. This blockwork is typical of late Pleistocene cryo-conditioning.
‡W. R. Browne "Pleistocene Glaciation in the Commonwealth of Australia" International Glaciological Society, **3**(22):111-115. (1956)

Figure 9.13a **View northeastwards from the upper catchment of Merrits Creek, Kosciuszko National Park.** The blockfield in the foreground is mostly comprised of Mowamba granodiorite blocks on a west facing slope with gradient of about 10%. The blocks of Mowamba Granodiorite have migrated downslope from solid outcrop visible in the background on the Rams Head Range. The abrupt edge to the granodiorite bedrock above is separated from this blockfield by a fairly planar terrace vegetated by grasses/forbs. This stepped terrain is typical of a cryoplanation terrace and provides context to this blockfield as a product of prior cryo-conditioning. Near the lower,distal edge of this blockfield, this writer found a striated block of quartzite at GR 166633 which suggests that glacial ice may have migrated eastwards from the Main Range as far as here and may have overtopped the saddle in the Rams Head Range at GR 166362; but at a time prior to the cryo-conditioning associated with this blockfield. This blockfield has migrated over and perhaps incorporated some older glacial debris.

Figure 9.13b **View northwestwards across the blockfield illustrated in figure 9.13a**.
This view down Merrits Creek towards the Snowy River looks side-on at the blockfield. The imbrication evident here suggests movement of blocky debris downslope, from right to left, consistent with gelifluction.

Figure 9.14 **View down upper Wrights Creek with blockstream descending from near GR 193654.**
The blockstream in the foreground has a concave cross-section and seems to have deflated below the adjacent banks of vegetated blockslope. This probably represents a form of thermokarst. The terrain steps down to the middle portion of Wrights Creek which then tips over a waterfall centred on a smoothed U shaped abrasion typical of glacial abrasion. David (1908)‡ recognised this hanging valley in Wrights Creek and suspected it was a glacial tributary of ice moving into upper Spencers Creek. Most of the valley floor in the mid-ground is vegetated blockfield/blockslope on Mowamba granodiorite bedrock typical of much of the elevated terrain underlain by Mowamba granodiorite in the Kosciuszko National Park.

‡ T. W. Edgeworth David "Geological notes on Kosciusko, with Special Reference to Evidences of Glacial Action", *Proceedings of the Linnean Society of New South Wales*, 1908, Vol **xxxiii**, part 3, reference to a hanging valley on the southeast side of Spencers Creek on p664.

End of Chapter Nine.

Chapter Ten Time-Out

This chapter considers climate proxies from southeastern Australia, the Pacific Ocean and Antarctica using a variety of methodologies. These proxies all point to coincident periods of cold, dry and windy conditions which have cycled through the late Pleistocene epoch at times which correlate with blockstream/blockslope development as well as a limited glaciation in the Kosciuszko region.

This chapter also attempts to demonstrate specific climatic conditions associated with active blockstream development and alluvial fan development in the northern hemisphere. The MAP (Mean Annual Precipitation) and MAAT (Mean Annual Air Temperature) associated with the survival of discontinuous permafrost gives us the means to estimate the magnitude of cooling in our highlands during the last cold phase of the late Pleistocene.

Closer to home: the nature of sedimentary debris buried beneath modern soil on the summit flat of Mt Nelse, on the Bogong High Plains, Victoria; the chronostratigraphic investigation of Megalake Bungunnia; relict alluvial fan debris at the margins of our Highlands; as well as the investigation of former Equilibrium-Line-Altitudes of prior Tasmanian glaciers, all provide valuable and consistent evidence.

In chapter 8 we discussed the Kosciuszko Moraines associated with the cirque-like glaciation, which have been dated by Barrows et al (2001). The dated inner moraines at Cootapatamba and Blue Lake range from 16ka-20ka (Barrows et al 2001, table 1)[99] and compare well to the Last Glacial Maximum (LGM) calculated by Barrows et al (2002)[100]. Exposure dating of Tasmanian and Kosciuszko moraines has tightly constrained LGM exposure ages within 17ka-20 ka. The outer moraines associated with this cirque-like glaciation at Kosciuszko, are older and have probably been modified by cryo-conditioning. Barrows et al (2001) may regard these outer moraines associated with Blue Lake to be 59.3ka +/- 5.4 ka, but this does not correlate well with palaeoclimatic markers.[101] The minimum carbonate content % and minimum sea surface temperature from the Deep Sea Drilling Project at site 594, all align with 60-70 ka before present and also align with the minimum in the deuterium record of the Vostok Ice Core; as per Barrows et al (2001) figure 5.[102] All these minimums point towards a time of minimum atmospheric temperature and maximum cooling, for the cold phase prior to the LGM, which are necessary for ice preservation, be that glacial ice or sub-surface permafrost ice. The maximum exposure ages obtained for blocks in the outer moraine (BL-I) by Barrows et al probably relate to cryogenic reworking of this outer moraine rather than its initial deposition, which suggests that the outer moraine is slightly older than the exposed blocks and probably correlates within 60-70 ka, but older than 61.7ka as discussed in chapter 9.

At the same time that these small cirque-like glaciers were active within a very restricted area of approximately 16 km² in the Kosciuszko area, there was also cryogenic activity affecting large areas of the elevated terrain in Kosciuszko National Park (KNP). Barrows et al (2004) dated exposed blocks on a narrow, steep blockstream below Section Ridge in the northern reaches of KNP.[103] The four exposure ages for these blocks ranged from 17ka-23ka. To the southwest of KNP near Mt Hotham, Victoria, exposure ages of blocks in the proximal block glacii at Mt Little Higginbotham ranged from 16ka-21ka and a block at the distal end of blockstream A, recorded 59ka of exposure.[104] These cryogenic block deposits at Hotham are illustrated in the *Kosciuszko Photoglossary*.

Despite the limited sampling range, these cosmogenic exposure ages provide consistent evidence that in terrain above 1000m in the Kosciuszko region of NSW, Victoria and Tasmania, permafrost was active during the late Pleistocene and was contemporaneous throughout these terrains.

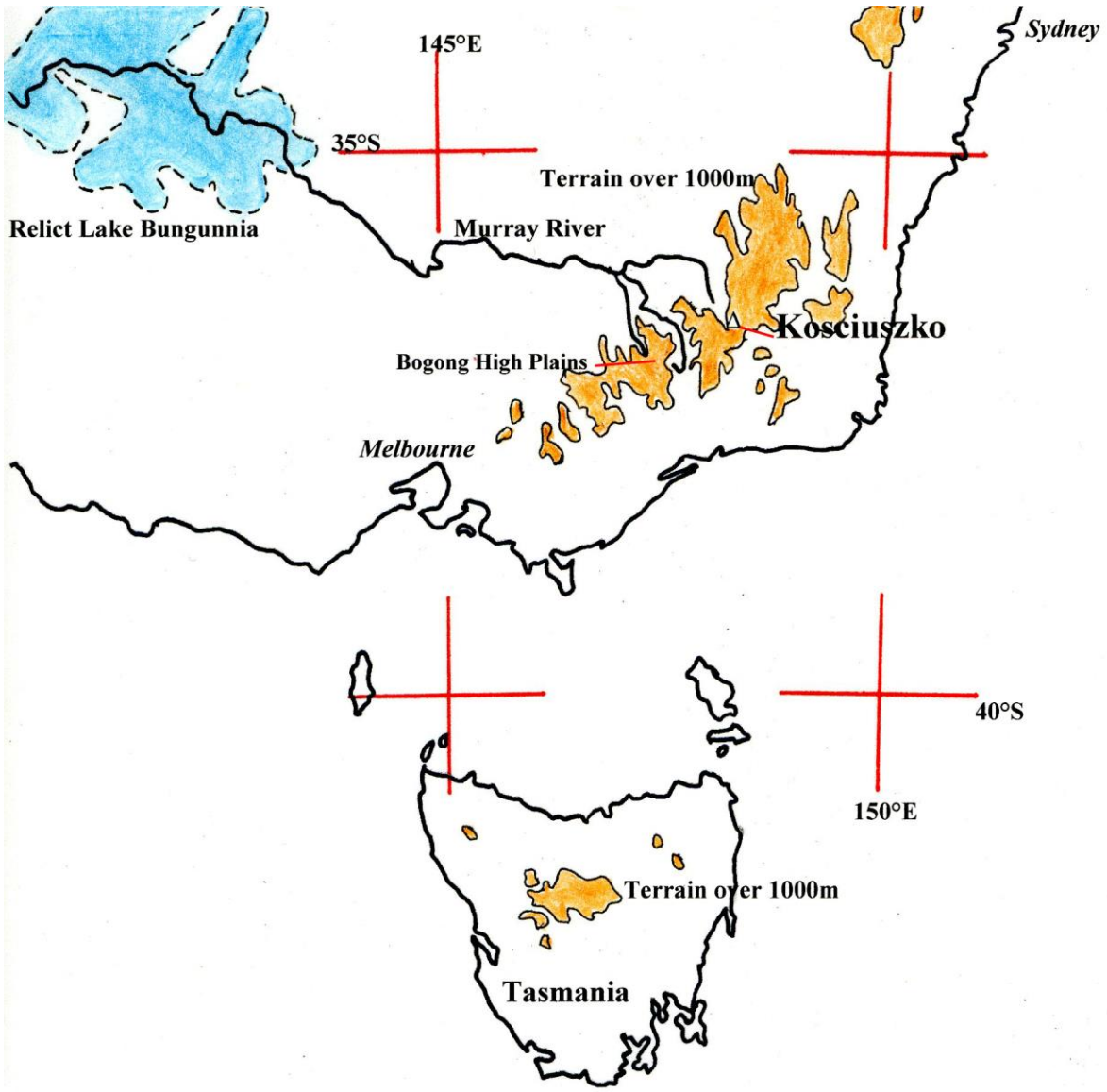
An exploration of climate proxies in south-eastern Australia is necessary to appreciate why glaciation at Kosciuszko was so marginal and why permafrost appears to have been so pervasive across the KNP, during the late Pleistocene. It is also necessary to explore palaeoclimate prior to the late Pleistocene in order to discover a potential window, for the existence of a possible Ice-Field over the Kosciuszko Main Range, which appears to have generated small valley glaciers radiating out from Kosciuszko at a time preceding the late Pleistocene.

The sedimentary evidence for this scenario is substantial, despite being fragmented; but looking back in time, the view will always be restricted and distracted by processes that have shaped this landscape in the interim. Lastly, we will look at climatic conditions necessary to promote and sustain permafrost and the associated cryogenic features: *blockstreams, blockslopes and rockglaciers* based on research into active examples located in the Swiss Alps, Eurasia and Iceland. This would be in keeping with James Hutton's premise that ***the present is the key to the past*.**

Figure 10.1

Outline Map of southeastern Australia showing relict megalake Bungunnia.

Most of the terrain above 1000m on mainland Australia was affected by cryo-conditioning during the late Pleistocene, whereas in Tasmania most of the terrain over 1000m was glaciated except those outliers in the E&NE, which suffered cryo-conditioning during the late Pleistocene due to lower precipitation. The now relict Lake Bungunnia occupied a large area within the lower Murray Basin during the early Pleistocene and the sediments trapped there allow us to reconstruct past landscapes and climate.



Megalake Bungunnia

Sandra McLaren and Malcolm Wallace investigated Plio-Pleistocene climate change and the onset of aridity in southeastern Australia. Sediments of the now relict Lake Bungunnia provide one of the most continuous records of terrestrial sedimentation in the Plio-Pleistocene interval in southern Australia. The Blanchetown Clay was the main depositional unit of Lake Bungunnia. At its base is the Chowilla Sand, a freshwater fluviatile unit dating back to 2.4 Ma. Below the Blanchetown Clay is the Karoonda Surface, a major ferricrete surface and unconformity, which is indicative of erosion under warm, climatic conditions during Miocene-Pliocene times, prior to 2.4 Ma. The regular influx of water into Lake Bungunnia during the early Pleistocene allowed the deposition of clay and fine sand that make up the Blanchetown Clay, and is also indicative of "*average rainfall 2-3 times that of the present day*", according to McLaren and Wallace.[105]

The key to this investigation was the examination of the Nampoo Member, which occurred towards the top of the sedimentary sequence comprising the Blanchetown Clay. The Nampoo Member consists of quartz silt, with consistently fine grained and well sorted grains of quartz with a modal grainsize of 20-25 microns, typical of wind-blown sediment.[106]

McLaren and Wallace have quite rightly inferred that this significant layer of "*loess"* towards the top of the Blanchetown Clay may be the first sedimentary evidence of the development of extensive dune systems in south-eastern Australia, which marks a major shift in climate for the region.

Magnetostratigraphic evidence based on the recognition of reversals in the earth's magnetic field, has been established for the sequence of sediments that make up the Blanchetown Clay. The Nampoo Member of the Blanchetown Clay has been constrained to 1.4-1.5 Ma which puts it about mid Pleistocene.[107] Look for the text box below which explains magnetostratigraphy and MIS or Marine Oxygen-Isotope Series.

McLaren and Wallace also investigated the overlying Bungunnia Limestone which overlies the Blanchetown Clay and marks the progressive demise of the now relict Lake Bungunnia during the late Pleistocene. The progressive reduction in lake level recorded in the Bungunnia Limestone since 1.2 Ma, correlates with oscillations in marine oxygen-isotopes and implies an overall trend of increasing intensity of arid climatic regimes, during the remainder of the Pleistocene epoch.[108] This is significant and it correlates well with the development of longitudinal sand dunes of the Woorinen Formation in the western Murray Basin as well as the development of fine wind-blown particles in sediments of the Tasman Sea during the late Pleistocene (discussed below).

Tasmania: The glacial record

Eric Colhoun, Kevin Kiernan, Timothy Barrows and Albert Goede reviewed Tasmanian glacial moraine distribution and the ages of moraines based on a variety of methods and published in 2010.[109] Colhoun et al concluded that Tasmania had a complex history of Quaternary glaciation with many ice advances during the early, middle and late Pleistocene, with the possibility of even some older moraines going

back to Oligocene and Pliocene times, (prior to 2.5 Ma). Each known ice advance during the Pleistocene covered a smaller area than the preceding one.

During the early Pleistocene, ice covered about 7000 km² of the Central Plateau and western mountains with maximum ice advance at 1 Ma ago and maximum ice thickness of 500-800m close to and west of the Central Highlands.[110] Ice advances also occurred several times during the last 100ka, with ice cover during the LGM at Marine Isotope Stage MIS-2, estimated at around 1100km².[111] (*see text box below for explanation of MIS*)

Since ice cover is dependent on precipitation, this scenario of decreasing ice-cover correlates with McLaren and Wallace's report of a progressive decline in precipitation since 1.2Ma ago for southeastern Australia.

The southwesterly maritime influence on Tasmanian glaciation is supported by the attenuation or reduction in cirque development and diminished ice thickness of the ice-cap towards the east of Tasmania. Also, as one moves from the southwest towards the northeast, the snow-line rises and precipitation decreases into the rain shadow.[112]

Climatic inferences for glacial periods during the Pleistocene are based on former Equilibrium Line Altitudes (ELA) for Pleistocene glaciers. The ELA is an estimate of the altitude where ice is accumulating above the ELA and melting below the ELA.

Colhoun et al calculate a depression of 6.5°-10° C in MAAT (Mean Annual Air Temperatures) for the late Pleistocene compared to the present day which would have depressed snow lines 1000-1500m. The larger ice advances of the early Pleistocene may have required MAAT 1°-2° C lower than the LGM at MIS-2, with snow lines another 150m-300m lower.[113]

Given there was a peak in glacial activity in Tasmania at about 1Ma before present and the extent of this activity was about 7000km² or about 6 times greater than the 1100km² of glaciation during the LGM, then we could expect to find a proportional response for glaciation at Kosciuszko. Mapping of the moraines and associated cirques at Kosciuszko for the LGM indicates a maximum footprint for glaciation at Kosciuszko of 15km² (Barrows et al 2001)[114] to 16km² (Minty 2016, unpub)[115].

The fragmented evidence for an earlier ice-cap/valley glaciation at Kosciuszko mapped by this writer, is estimated to cover 100-150 km². A *proportional response* would be about 100km² for glaciation at Kosciuszko corresponding to the peak in Tasmanian glaciation at about 1Ma ago. The rather restricted response to glaciation at Kosciuszko was probably constrained by available precipitation as supported by McLaren and Wallace (2011). What other evidence do we have to support this assertion of increasing aridity in southeastern Australia during the late Pleistocene?

DIRTMAP: The geological record of dust.

Kohfeld and Harrison presented their *DIRTMAP: the geological record of dust in 2001*.[116] Their figure 1 presents aeolian accumulation rates from the Chinese Loess Plateau with a sediment record in the Pacific Ocean and inferred air temperatures from the Vostok Ice Cores. There is a simultaneous correlation of peak accumulation rates of dust at these three sites during the cold phases defined by Marine Oxygen Isotope Stages: MIS-2,4,6,8 and10, during the last 400,000 years.[117]

This demonstrates that repeated cold, dry and windy phases of climate during the mid-late Pleistocene have been a global phenomenon. With respect to Australia, these dust records southeast of Australia, suggest a 2-9-fold increase in deposition rates between 16ka and 23 ka ago.[118] Also, an increase in the coarse fraction of terrigenous material deposited in the Tasman Sea at this time may reflect a reduction in dust rainout events, associated with a more arid/cold climatic phase.[119]

This correlation at 16ka-23ka aligns precisely with cosmogenic exposure ages for blocks exposed in cryogenic block deposits in the highlands of NSW, Victoria and Tasmania, when permafrost is suspected of being active.

Cold, dry and windy conditions coupled with elevated conditions in the Highlands of southeastern mainland Australia would have contributed to the *thermal regime* required by permafrost 16ka-23ka years ago. *The specific conditions in areas with active blockstreams will be discussed a little further on*.

Palaeodunefields of the western Murray Basin

Lomax, Hilgers and Radtke (2011) present palaeo-environmental change recorded in the dunefields of the western Murray Basin since 380ka. *Phases of substantial dune sand deposition were identified for periods 18ka-38ka and 63ka-72ka before present.*[120] Older periods exist but are poorly resolved. Phases with high aeolian sedimentation rates coincide with more arid conditions as was the case with fine aeolian sediments recorded by the Deep-Sea Drilling Project in the Tasman Sea by Kohfeld et al (2001). The phases of dune building/aridity reported by Lomax et al also coincide with cosmogenic exposure ages for cryogenic block deposits in Australia as well as the restricted glacial deposits (Kosciuszko Moraines) reported by Barrows et al in 2003 and 2001 respectively.

Present day winds have a strong southwesterly component, indicating that the linear Woorinen Formation dunes of the Murray Basin are relict forms and were generated under palaeo-wind regimes with a stronger westerly component.[121] The Woorinen Formation is underlain by a sedimentary sequence (the Blanchetown Clay) which was deposited in the large freshwater palaeolake, Bungunnia. Its demise coincided with a major shift from more humid to more arid conditions, which led to the development of the Murray Basin dune fields.

The grouping of Optically Stimulated Luminescence (OSL) ages for sand particles at four different sites by Lomax et al (2011), implies that dune formation in the western Murray Basin was not continuous, but occurred within defined phases separated by periods of landscape stability. This is in keeping with the global climate cycles of the late Pleistocene and the exposure dating of blockfields/blockstreams above 1000m.

In conclusion, the arid, cold and windy phases during the last 400,000 yrs as defined by the MIS-10, 8, 6, 4 & 2, became progressively more arid which controlled and diminished the accumulation of ice at Kosciuszko during the late Pleistocene. The absence of a thick insulating layer of snow, which would have off-set cooling of the ground beneath, allowed cryo-conditioning to dominate in the elevated terrain of Kosciuszko National Park. Conditions during MIS-4 and MIS-2 would have maximised cryo-conditioning of elevated terrain with intense reworking of any earlier exposed moraines as is evident from their present condition.

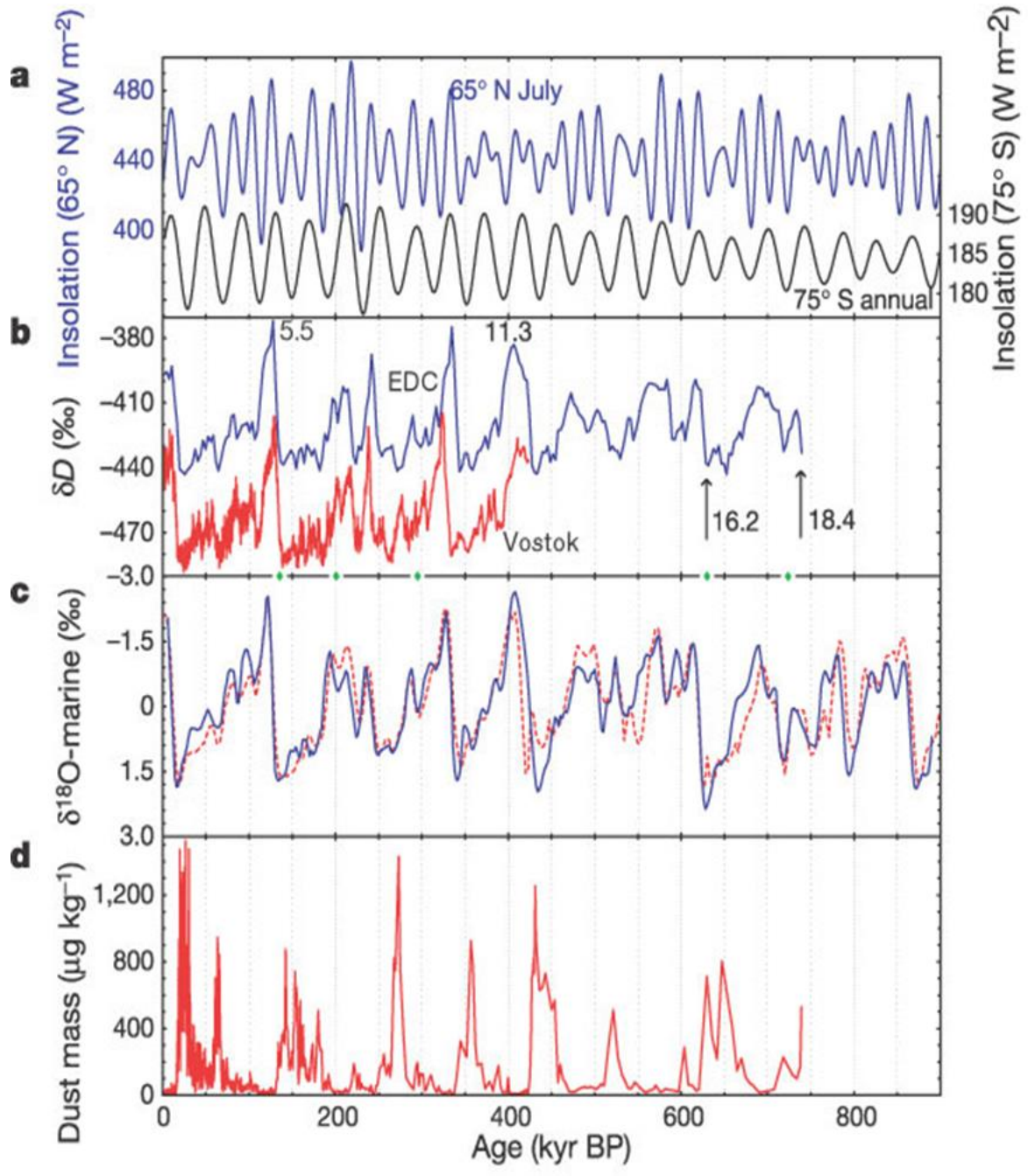


Figure 10.2 Analysis of Antarctic Ice Cores

Authors of Figure: Graphs based on analysis of EPICA Dome C (EDC) and Vostok Ice Cores

Augustin, Laurent & Barbante, Carlo & Barnes, Piers & Barnola, Jean & Bigler, Matthias & Castellano, Emiliano & Cattani, Olivier & Chappellaz, Jérôme & Dahl-Jensen, Dorthe & Delmonte, Barbara & Dreyfus, Gabrielle & Durand, Gael & Falourd, Sonia & Fischer, Hubertus & Flückiger, Jacqueline & Hansson, Margareta & Huybrechts, Philippe & Jugie, Gérard & Johnsen, Sigfus & Zucchelli, Mario. (2004). EPICA Members, Eight glacial cycles from an Antarctic ice core. Nature 429, 623-628. Nature. 429. 623-8. 10.1038/nature02599.
This figure was downloaded on 28th July 2020.

Explanation of some modern concepts in Stratigraphy

Magnetostratigraphy

The earth's magnetic field is not permanent. It has undergone regular reversals throughout time, at which times North becomes South and South becomes North. It was only in the mid 20th century that Jan Hospers produced a convincing study of Icelandic basalts which demonstrated that reversed magnetism in these basalts was a record of time when the earth's magnetic field had a reversed polarity and that this pattern of reversals could be a powerful stratigraphic tool. The first geomagnetic polarity time-scales began to take shape when the combined use of radioisotope dating and magnetostratigraphy was adopted on lava flows. Radioisotopes which start decaying immediately after crystallisation in a lava rock, can be analysed to give accurate dates of crystallisation because these isotopes decay at known rates.

During the rock forming process another process is also active which allows us to measure the alignment of the earth's magnetic field. Common, iron-rich, magnetic minerals align themselves with the earth's magnetic field and are subsequently locked into the rock system on cooling, thereby preserving the natural remanent magnetic signal. This can occur in quite diverse rock types. It occurs for the mineral magnetite suspended in a volcanic lava flow and it can also occur with magnetite in sediments.

Fine grained magnetic minerals washed into a lake, (like megalake Bungunnia during the early Pleistocene), will align themselves with the earth's magnetic field while suspended in the water column and also in the soft water saturated, top-most layer of sediment, on the floor of the lake. Fine grained sediment and calm settling conditions, which would have existed throughout the deposition of the Blanchetown Clay at Lake Bungunnia in the lower Murray Basin during the early Pleistocene, would have maximised the preservation of the earth's magnetic signatures during that period. These patterns of Normal and Reversed polarity are like a fingerprint and this is what McLaren and Wallace used to constrain the age of the Nampoo member to between 1.4Ma & 1.5Ma within the Blanchetown Clay, to define the turning point in climate change during the Pleistocene for southeastern Australia.

[Remember: 1Ma means 1 million years ago].

I paraphrased parts of the following paper to write this short account:
Cor G. Langereis, Wout Krijgsman, Giovanni Muttoni, and Manfred Menning, "Magnetostratigraphy-concepts, definitions, and applications", *Newsletter on Stratigraphy* **43**(3), (2010):207-233.

Explanation of some modern concepts in Stratigraphy

Oxygen Isotopes and the **M**arine **I**sotopic **S**tages (**MIS)**.

The Marine Oxygen Isotope Stages (MIS), are a dated sequence of sediment ages based on the ratio of Oxygen 18 to Oxygen 16 isotopes within the marine sediments. The proportion of Oxygen 18 increases in the carbonate casings of marine organisms trapped in deep sea sediments when sea surface temperatures are low due to global cooling. This response is caused by the preferential uptake of Oxygen 16 in water molecules accumulating in expanding ice sheets during these global cooling events. The reason for this is the preferential evaporation of water molecules with the lighter oxygen 16 isotopes, under cold conditions. As atmospheric moisture moves towards the poles, water molecules with oxygen 18 isotopes are preferentially distilled by precipitation back into the ocean while the remaining water vapour, enriched with oxygen 16 isotopes continues towards final precipitation at the polar ice cap.

These fluctuations recorded in deep sea sediment cores correlate well with terrestrial evidence of glacial/interglacial periods from ice-cores and also relate to the Milankovitch cycles which control variations in insolation over the past one million years. The figure 10.2 above compares insolation (heat from sunlight); Deuterium content from ice cores (which is a proxy for temperature); Oxygen 18 variation-MIS, and dust content of ice cores. The MIS numbers start from the present and work back in time. The even numbers correspond to periods of relatively cold climate. The LGM or last glacial maximum, occurred during MIS 2.

Deuterium in Heavy Water as a proxy for MAAT (Mean Annual Air Temperature).

Deuterium or heavy hydrogen has two heavy particles in each nucleus compared to the dominant form of hydrogen which has only one heavy particle, (a proton) in each nucleus. Only about 156 atoms of deuterium are present in every 1,000,000 atoms of Hydrogen under natural conditions. *Heavy-Water* made from two Deuterium atoms and one atom of Oxygen is only 11% heavier than ordinary water molecules but this variation in density means that naturally occurring *heavy-water* suffers a similar fate to water made from oxygen 18 isotope, instead of the more abundant and lighter oxygen 16 isotope. Therefore, under cold climate conditions, heavy-water gets enriched in the ocean and depleted in moisture precipitated at the poles leading to a decrease in Deuterium trapped in ice cores. Refer to the changes in Deuterium recorded in the EPICA Dome C (EDC) and Vostok Ice Cores in figure 10.2 above. Decreases in Deuterium within the ice-cores correlate with colder conditions.

The symbols below are used in figure 10.2 above.

δ**D**= change in Deuterium, which is a proxy for atmospheric temperature change.

δ18**O**=change in ratio of 18**O**/16**O** for oxygen isotopes in ocean sediments, which is a proxy for ocean temperature.

Active cryogenic processes in the northern hemisphere.

Washburn (1979) presents a map (his fig 6.23) of the distribution of active blockfields, blockslopes and blockstreams after Frenzel (1959) for northern Eurasia.[122] Of the 47 locations marked, 18 are located in high relief, high altitude terrain on the south-eastern flank of the Russian Federation, both west and east of Lake Baikal. All 18 of these locations are within the present permafrost zone. Three of the seven locations in the Urals lie within the present permafrost zone. The other sites are scattered along the northern frontier of the Russian Federation in moderately elevated terrain, well within the permafrost zone, except for one outlier which sits in elevated terrain on the North Korean border, well outside the mapped permafrost zone. Despite a few outliers, there is a strong association between *active blockstreams* and *permafrost* in northern Eurasia.

Stuart A Harris (1994) has classified cryogenic (periglacial) landscapes into three groups based on dominant features: *active blockstreams, active rock glaciers and active gelifluction dominated landforms.*[123] Harris has also described the zonation of these landforms in mountainous permafrost based on distinct ranges of mean annual air temperature (MAAT) and mean annual precipitation (MAP). His plot of MAAT and MAP in his figure 13, differentiates the three cryogenic (periglacial) landscapes with only small overlaps.[124]

Harris (1994) presents examples of climatic data in his table 1, for these three sets of mountain permafrost landscapes. The MAAT of all the weather data for all active blockstreams plotted are less than -6°C.[125]

Harris (1994), concludes his description of active blockstreams by noting that active blockstreams always occur in the ***active layer*** overlying ***permafrost*.**[126] The gelifluction and blockstream zones in Harris's distribution of climatic parameters join where the MAAT is about -6°C and MAP ranges from 100 to 400mm.[127] The gelifluction zone requires slightly warmer and wetter conditions than the blockstream zone, **but *the junction line suggests an approximate common climatic condition for gelifluction and blockstream activity which may simulate conditions on the Bogong High Plains at 16ka to 23ka ago, based on the coexistence of relict blockstreams and gelifluction layers in this region****, (illustrated in Ch. 9).*

Investigation of the factors controlling the distribution of permafrost in Canada by Smith, M.W. and Riseborough, D.W. (2002), demonstrates how the relationship between MAAT and MAGT (Mean annual ground temperature) in permafrost is affected by snow cover, vegetation, topography and soil conditions. The relationship between permafrost and climate is not simple but with respect to the discontinuous permafrost zone, Smith and Riseborough predict that permafrost is generally absent at sites with mineral soil at MAAT's above -2°C.[128]

Etzelmuller et al (2007), after researching the distribution of mountain permafrost in Iceland, determined that the threshold for the existence of permafrost is about minus 3°C MAAT.[129] Iceland has a sub-polar maritime climate with widespread mountain permafrost and also possesses a broad range of

periglacial landforms including: blockfields, gelifluction sheets/terraces/lobes, blockstreams, nivation hollows, cryoplanation terraces, thermokarst features, patterned ground and rockglaciers, (Priesnitz, K. and Schunke, E., 1983). Priesnitz and Schunke did not justify the possible role of permafrost in the genesis of these periglacial landforms nor consider the existence of relict or inactive periglacial forms.[130] However, Agust Gudmundsson did *examine and correlate the distribution of active rockglaciers within the mountain permafrost zone of Iceland* in Etzelmuller et al. (2007). Agust also points out that active and relict rock glaciers are most prevalent within the rain shadow zone of the highlands of northern Iceland.[131]

In conclusion it is reasonable to assert that *active blockstreams, rockglaciers and gelifluction are dependent on a permafrost thermal regime and that the MAAT during the LGM on the Bogong High Plains where blockstreams and gelifluction lobes appear to have co-existed, was about minus 6^{o} C*. The most elevated examples of relict blockstreams and gelifluction sheets occur close to 1800m asl on the Bogong High Plains. The MAAT at Falls Creek weather station (1765m asl) near Basalt Hill on the Bogong High Plains is currently 5.9^{o}C. This suggests a reduction in MAAT of 11.9 during the last cold phase at 1765m.

The termination of a large relict basalt blockstream at 1420m southeast of Basalt Hill (GR:0528532/5916454) at the end of the last cold phase, suggests that 1420m corresponds to a prior minus 3^{o}C isotherm, (based on Etzelmuller et al 2007). This allows us to calculate an 11^{o}C drop in MAAT for Basalt Hill on the Bogong High Plains during the period 16ka-23ka before present when these blockstreams were probably last active. This compares well to the estimated 11.9^{o}C reduction against present MAAT based on the observations by Stuart A. Harris with respect to specific zones of the permafrost environment.

Evidence of relict gelifluction on the Bogong High Plains

The treatment of relict cryogenic features in the highlands of New South Wales, Victoria and Tasmania in Chapter 9 was limited to the very visible block deposits that form blockstreams, blockslopes and lobate rock glaciers. There is also evidence of *frost-creep* and *gelifluction* from the now buried layers of weakly stratified cobbles beneath alpine humus soils, and below the now vegetated surfaces of the Bogong High Plains which did not develop extensive blockwork.

Thin but extensive layers of competent, angular debris were discovered by auger samples along a set of surveyed traverses radiating out from the summit of Mt Nelse, 1882m asl., (Minty 1989).[132] These materials are described below. Mt Nelse has a very smoothed appearance and outcrops of its quartz schist bedrock have very low relief. This rock type has been less susceptible to production of large volumes of coarse blocks than basalt, dolerite or granodiorite bedrock which occur elsewhere on the Bogong High Plains. The surface is well vegetated except for the exposed, almost flat summit area which has a patchy feldmark community of dwarfed heath with bedrock, at or close to the surface.

Alpine humus is a dark, organic, sandy loam soil usually 200-300mm depth which carpets the underlying stony layer of competent gravel, cobbles and blocks, which has migrated away from the summit. This stony layer in turn overlies extremely weathered bedrock with much of its crystal fabric converted to clay.

The alpine humus topsoil has developed during the Holocene with warmer and wetter conditions than the preceding Pleistocene cold phase. The evidence for this is reported by Hope et al, (2012)[133] in their study of peat forming bogs and fens of the Snowy Mountains of NSW. These bogs and fens act as repositories of organic matter from the surrounding alpine terrain. Calibrated Carbon dates for the initiation of deposition of organic debris in the Kosciuszko National Park are tabulated in their table 14. Between 12,000 and 8,500 years BP, they conclude that peat formation had begun at a wide range of sites and that adjoining slopes had become stabilised by the current vegetation. They also state that even on elevated alpine sites at about 2000m, the original feldmark vegetation had been replaced by closed alpine herbfields or heath by about 10,800 years BP. This vegetation cover provided organic matter and also a sediment trap for surface wash and wind-blown debris which contributed to the development of our present alpine humus soils.

The above investigation by Hope et al, 2012 has established that the stony layer and mineral detritus beneath the alpine humus top-soil at Mt Nelse and other similar terrain, must be pre-Holocene in age. There are some characteristics of the sheets of gravel, cobbles and blocks which extend outwards from the summit of Mt Nelse beneath the alpine humus, which suggest a cryogenic origin.

The Mt Nelse summit area is a broad, gently sloping bedrock surface made of closely jointed and foliated quartz schist and migmatite. Small scarps and terraces occur right around the summit bedrock area comprising about 40 Ha. Beyond the summit bedrock flat and down towards the 1830m contour is a further set of concentric terraces and risers with a modest load of coarse angular debris, now vegetated by open heath.

Gently stepped, broad, vegetated sheets of coarse angular debris overlain by alpine humus soil and open heath extend southwards to about 1740m. To the east is the large snow patch zone between the 1780-1840 contours which can be regarded as a large cryogenic step in the terrain with other smaller steps and hollows excavated below, out of bedrock, in the vicinity of perennial springs on this steep east facing slope below Mt Nelse. Most of this terrain on Mt Nelse is interpreted as *relict cryoplanation terrain*.

Detailed surveys radiating out from the summit, support Washburn's description of cryoplanation terrain referred to in chapter 9. One of the survey lines from Nelse summit along 344^{o} extends over 285m with a gentle slope averaging 1.12^{o}. Within this gently sloping terrain two sets of auger samples were recorded to bedrock; with sieving and grain-size analysis carried out for each 100mm of sample extracted.

Stratigraphic site (6) at 65m north of the summit revealed three distinct layers. The upper (layer1) from 0-20cm below surface is a vegetated organic gravelly loam (alpine humus soil) with the dominant mineral being fine quartz sand (0.063-2.00mm).

Layer 2 from 20-40cm below surface, is frost sorted debris grading from cobbles/gravel/sand at the top of layer 2 to gravelly sand at the base of layer 2. The fine sand fraction contains some (<1%) small shards of glassy quartz suggesting impacts or fracturing of quartz grains. Only about 2% of layer 2 had fines <0.063mm and most of the coarse rock fragments were moderately weathered but competent. The layer 3 from 40-110cm below surface comprised extremely weathered bedrock with remnant silicate crystal fabric, which was readily penetrated by the hand operated auger due to conversion of feldspars to clay.

At stratigraphic site (7), 165m north of summit along survey line 344^{o}; layer 1 from 0-20cm below surface, was dark brown organic loam with quartz grains from 0.063mm-2.00mm comprising 77.8% of the sample. No fine shards of quartz were found in layer 1. From 20cm down to 60cm, layer 2 comprised pale orange-brown cobbles, gravel and sandy matrix at the top and grading down in grainsize with depth. Fines passing the 0.063mm sieve accounted for 1.8% of the sample at the top of layer 2 and 2.8% of the sample at the base of layer 2. Also, fine sand retained in the 0.063mm sieve increased from 11.8% at the top of layer 2 to 20.5% at the base of layer 2.

There appears to be a well-defined segregation of particles within layer 2 which is consistent with it being a prior *active layer within permafrost* as described by Arturo Corte, 1966.[134] Again, about 1% of the fine sand fraction of layer 2 comprised very fine glassy shards of quartz, consistent with wind borne impacts. The lowest, layer 3, from 60cm down to 156cm was pale in color and corresponded to extremely weathered bedrock in contrast to the moderately weathered but competent clasts in layer2. Stratigraphic site (9) at about 285m north of summit, lies at the distal edge of a distinct sheet of debris on a slope declining at 3^{o} towards the north. *This sheet-like layer of debris has been interpreted as a relict gelifluction layer.*[135]

Inspection of auger samples at site (9) revealed: layer 1 at 0-30cm depth consists of dark brown, gritty organic loam with few coarse clasts. Layer 2A at 30-45cm is a compact layer of platy blocks and Layer 2B from 45-60cm is pale orange-brown gravelly loam. The layer 3, at 60-103cm is pale greenish-brown, extremely weathered bedrock. Again, there is a grading within layer 2 with coarsest rock pieces at the top and finer debris towards the base. This grading is a characteristic of all three samples of layer 2 and is consistent with *frost sorting of the active layer in prior permafrost* as described by Arturo Corte, 1966, (referenced above). The presence of fine shards of quartz suggests strong windy conditions.

It is probably impossible to differentiate the two probable transport mechanisms {*frost-creep and gelifluction*} responsible for the transport of competent rock fragments over extremely weathered bedrock on slopes of 1^{o}-3^{o} during the late Pleistocene, as inferred here for Mt Nelse, but the geomorphology and stratigraphy of this lobe of debris at stratigraphic site (9)is consistent with being a *gelifluction sheet* and its association with stepped terraces which are interpreted as relict *cryoplanation*

terraces strengthens that inference. This gives moderate confidence in applying S. A. Harris's climatic parameters for an estimate of prior MAAT and MAP, as described above.

Evidence of alluvial fans at the margins of the Highlands of the Great Dividing Range.

The relict alluvial fans in the upper valleys of the Kiewa and Mitta Mitta River were discussed in chapter 9 and they have considerable relevance to our consideration of palaeoclimate.
From a stratigraphic perspective these alluvial fan deposits and gully fills correlate with the cryogenic deposits, especially the weakly stratified cobbles of layer 2 (the relict active layer), which is also overlain by recent soil.

The relict alluvial fan deposits are indicative of a time when precipitation was probably less than 50% of present precipitation. These deposits are pre-Holocene and some are logically equivalent to the basalt blockstreams and glacii at Basalt Hill which in turn have been tentatively correlated as 16ka to 23ka.

<u>There is also significant evidence of alluvial fan activity adjacent to the Snowy River near Island Bend at 1200m, in the Kosciuszko National Park.</u>
Galloway (1963) investigated sedimentary exposures, 1 mile north-east of Island Bend at GR450163 (Mil. 1:63 360) with a view to determining their origin; as it had been suggested that this material could be of glacial origin. Galloway concluded that the boulders in a matrix of gritty sand silt and clay and associated lenses of stratified granitic sand, had the form of a debris fan built up by mass movement from the adjacent steep slopes with intervals of surface wash.[136]

This writer has observed a section at Site Four on the attached Island Bend Map, figure 10.3 below and also other numbered sections in the vicinity. Most of these sections are located in cuttings through spurs indicating an inversion of relief since the deposition of this material.

The road section at Site Four (GR 343804) is about 8m high and shows parts of two main layers (layers 1&2) but with an uppermost capping of blockwork along the right-hand side of the illustrated section, figure 10.4. The upper layer (2) comprises angular to sub-angular blocks in a gravelly clay matrix. The blocks are mostly less than 1m maximum dimension with modal size 300mm to 500mm. A few blocks up to 3m across also occur. The provenance is local, being granitic with isolated quartz blocks but without any evidence of input from Ordovician metasediment. Much of the blocky upper layer (2) is clast supported, but a significant proportion is also matrix supported. Localised imbrication within the upper blocky layer (2) indicates a down-slope direction of movement in a westerly direction. The lower boundary of the blocky layer (2) is undulose and deepens to the south, but is difficult to see in its entirety due to vegetation and sliding overburden.

Figure 10.5 is a close-up view of site Four. The lower layer (1) at site Four is stratified with thin layers and lenses of pale clay 10mm-50mm thick and bands of gritty sand and gravel exhibiting graded bedding. This stratified layer with its thin irregular lenses of poorly sorted gravelly sand with undulose

boundaries is typical of transient **sheet flood facies** of alluvial fan deposition. The upper blocky layer (2) is typical of **debris flow facies** within alluvial fan deposition. These deposition modes require low sporadic precipitation and a high relief landscape unprotected by vegetation. This deposit has also been isolated over time by the development and incision of adjacent creeks which has left it relatively elevated on a spur instead of being in the mouth of a valley.
The sections at Sites One and Two on figure 10.3, comprise trough-like debris flows of matrix supported blocks. A thin stony layer, 600mm below the surface at Site Five with extremely weathered granitic bedrock beneath, indicates an old erosional surface while the massive, open-block accumulation/*block field* in the gully about 100m northeast of Site Four, just below 1200m asl represents cryogenic activity, which probably post-dates the debris flow/stratified deposit adjacent at Site Four. However, a curious feature at Site Four, (figure 10.4) is the appearance of an imbricated block layer above the debris flow along the top, southwestern half of this large exposure. This blocky layer, like the blocks in the gully just to the northeast are probably cryogenic deposits and may represent cryogenic reworking of layer 2.

At Site Six, there is a small exposure of stratified grit, sand and clay, similar to the lower layer (1) at Site Four, and at Site Seven there is another thinly developed stone line 300mm-600mm below the modern grey loam soil and above extremely weathered bedrock similar to Site Five.

In conclusion these sections are not indicative of glacial till although they do share some characteristics with glacial debris, but they do not seem to possess any erratic or foreign material. The bedding and sedimentary structures present in these sections indicate westerly transport towards the Snowy River down the west-facing slope which would not be consistent with glacial transport down the Snowy River. The provenance of the material in these sections is local and typical of Mowamba Granodiorite and contains no exotic material from upstream.

These exposures are typical of alluvial fan deposition, which would have been possible during prior cold dry periods, with sparse vegetation providing limited protection to the steep slopes adjacent to the Snowy River Valley. The block accumulation in the gully adjacent to and NE of Site Four is probably late Pleistocene, whereas the fan deposit at Site Four, seems older and probably predates the LGM.

To sum up our interlude with *Time-Out,* the palaeoclimatic evidence considered in this chapter suggests that during the interval 16ka-23ka before present, the Highlands of southeastern Australia were cold, dry and windy. Consideration of alluvial fans and cryogenic deposits during this period indicate that MAP was probably 100mm-400mm and MAAT was depressed by 11^{o}C-11.9^{o} compared to present conditions. The actual MAAT where evidence of gelifluction and blockfield development co-existed, was probably about minus 6^{o}C.

End of text for Chapter 10. Figures 10.3 to 10.5 follow.

Figure 10.3

ISLAND BEND MAP

Copied from Geehi Dam 8525-2N 1:25000

Topographic Map © NSW Department of Lands,2001. GDA 94 GRID.

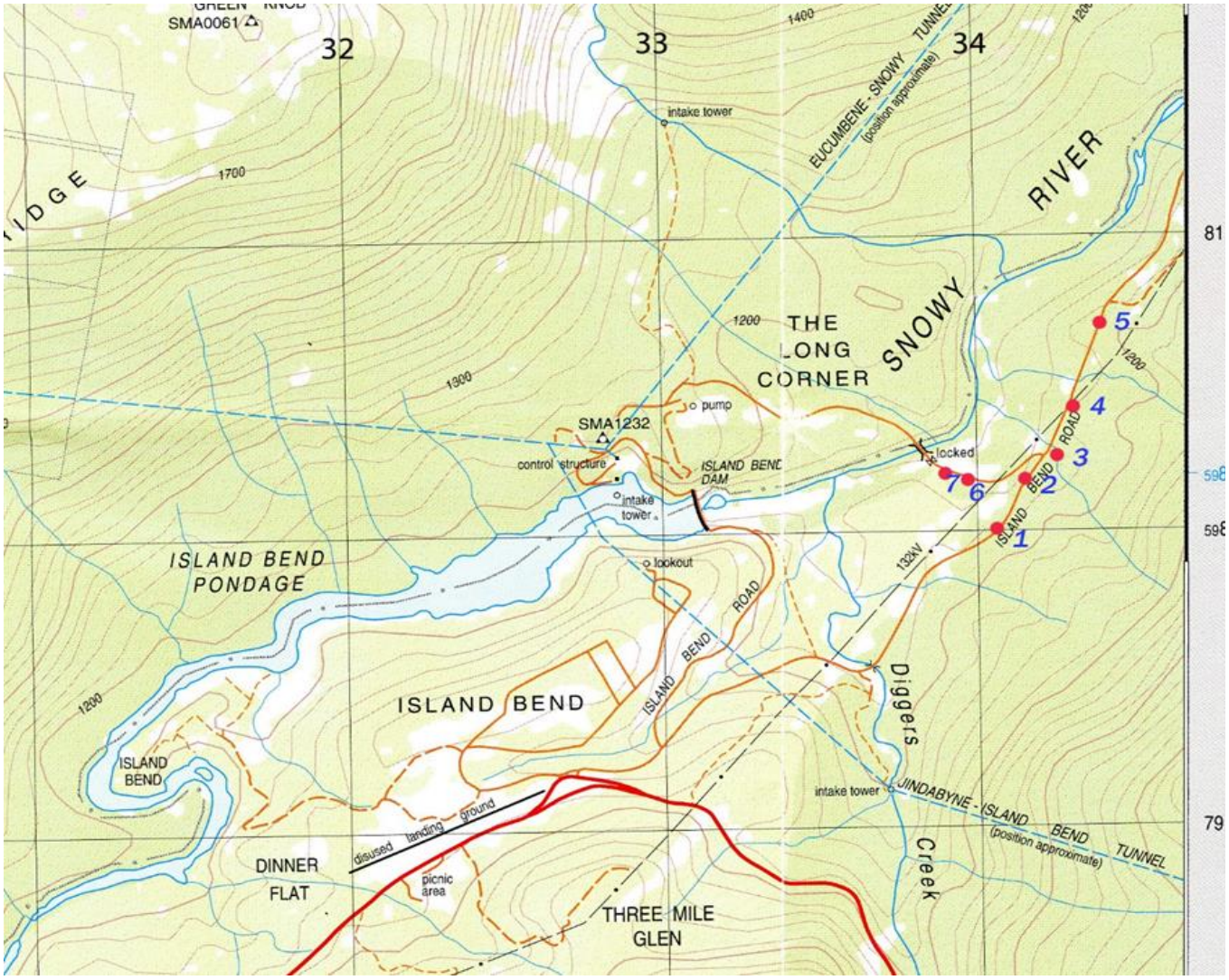


Figure 10.4. **Overview of road section at site 4, Island Bend**.
The red dots mark the boundary between layers 1 and 2. To the right, collapsed debris masks the underlying strata. Note that along the top of the section, especially the right-hand side, is a capping of blockwork. This suggests that alluvial fan activity and cryo-conditioning may have been contemporaneous here. This section is about 8m high and 30m wide for the portion in view.

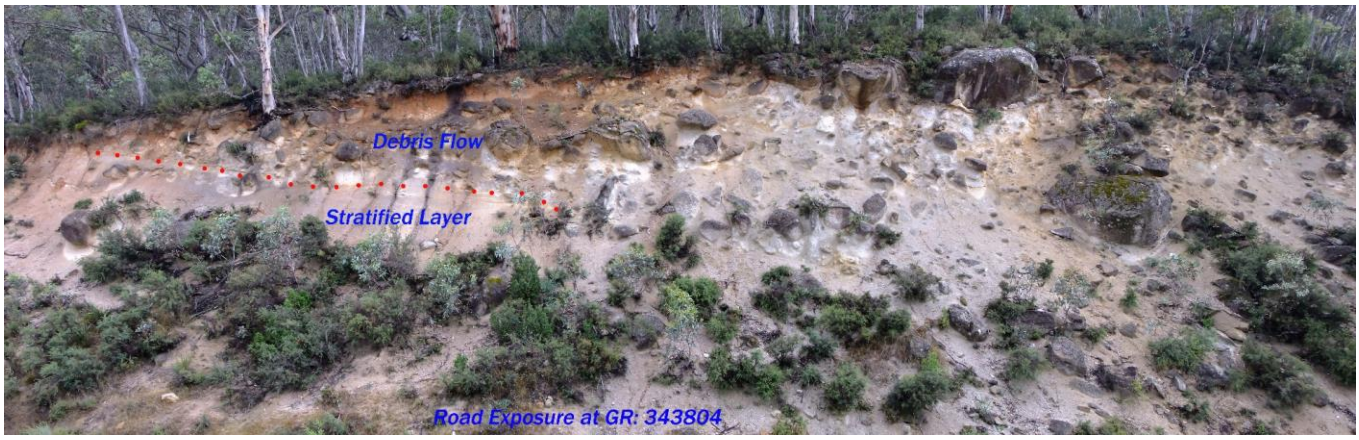
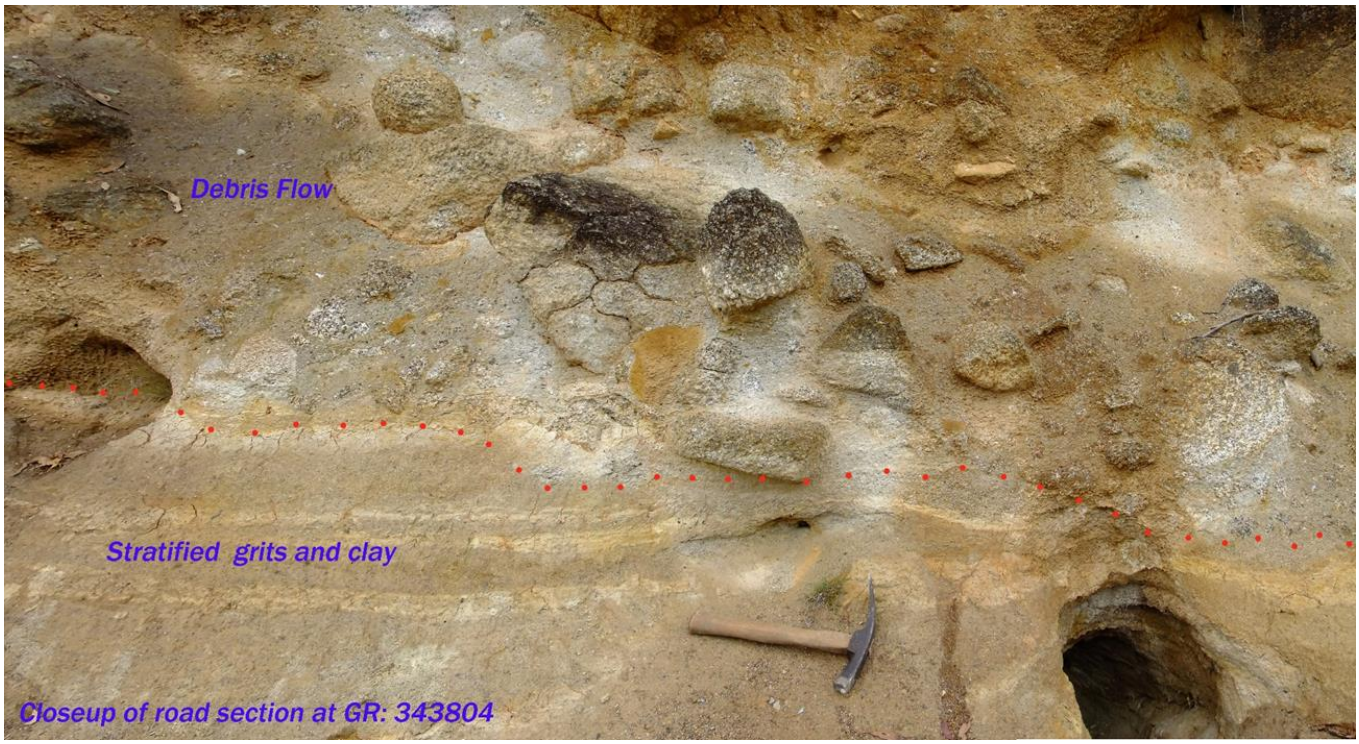


Figure 10.5. **Close-up of left-hand portion of the above section at stop 4, Island Bend**.
The red dots mark the undulating interface between layers 1 and 2. Most blocks are extremely weathered and the smaller ones are matrix supported. The debris flow (layer 2) appears to have eroded the underlying stratified grits and clay of layer 1.



Chapter 11 If it walks like a duck….

This chapter argues that there should have been a proportional response at Kosciuszko to the large-scale glaciation in Tasmania about 1 million years ago.

The evidence for ice-field glaciation should include erratic blocks carried by ice over topographic obstacles and deposited on bedrock of a different provenance.

Despite significant evidence having been submitted by David (1901), (1908) and Browne and Vallance (1957), (1963); a paper by R. W. Galloway (1963) refuted prior evidence of glacial erratics beyond the influence of the small cirques on the Kosciuszko Main Range. This paper by Galloway subsequently became the paradigm for glaciation at Kosciuszko when Galloway's map was published as a glacial inset map in 1990 with the BMR's *Geology of Kosciusko* Map.

This chapter examines evidence and arguments concerning a possible ice-field over the Kosciuszko Main Range predating the *Kosciuszko Moraines of the Last Glacial Maximum.*

In chapter 10, we suggested that there should have been a proportional glacial response at Kosciuszko to the glacial episode that encrusted 7000km² of the Tasmanian Highlands under an ice-cap at about 1Ma years ago, (Colhoun et al, 2010). During the last glacial maximum (LGM)at (17ka-20ka), Tasmanian glaciated terrain covered only 1100km² (Colhoun et al, 2010), while at Kosciuszko, on the Australian mainland in terrain up to 1000m higher than the glaciated terrain in Tasmania, glaciation was restricted to about 16km².

Palaeoclimatic evidence suggests that acute aridity was an issue in the Kosciuszko region during the LGM which restricted the accumulation of snow/ice, but the Tasmanian West Coast and Central Plateau were still subject to moist, oceanic air from the southwest with corresponding precipitation and accumulation of snow. The evidence from alluvial fans and relict cryogenic block deposits in the Kosciuszko National Park and Bogong High Plains, suggests a mean annual precipitation (MAP) of 100-400mm and an 11^{o}C-11.9^{o}C reduction in mean annual air temperature (MAAT) during the LGM. These cold, arid conditions were exacerbated and assisted by the strong, dry westerly winds that prevailed over southeastern Australia during the late Pleistocene.

A proportional response at Kosciuszko to the glacial event in Tasmania at 1Ma, would be about 6 times larger than the Kosciuszko glacial response during the LGM; which was about 16km². This ratio would suggest that Kosciuszko may have accumulated about 100km² of glacial ice at the same time that Tasmania accumulated 7000km² of glacial ice, approximately 1 million years ago.

Is there any evidence of glacial erosion or glacial debris at Kosciuszko beyond the well preserved evidence of the *Kosciuszko Moraines*?

Edgeworth David thought so in 1908. By then he had observed large scale erosional landforms and glacial erratics well beyond the influence of the recent cirque-style glaciation. He concluded: "*At a period of time, ...possibly 200 000 years ago Kosciusko was gradually covered by great fields of neve and glacial ice, and all but the Nunatakr of the Etheridge Range, were completely shrouded in the ice-cap. The snow field [ice-field] moved chiefly in a SE direction pouring its ice over what is now a precipitous escarpment leading down into the Thredbo Valley.... the maximum glaciations may have extended northwards as far as upper Diggers Creek... There now followed a considerable recession of the ice-sheet; the glaciated surfaces near Lake Albina belong perhaps to this stage. Next we find in far more recent geological time, perhaps removed by only 10 000 to 20 000 years from the present, evidence of a fresh and conspicuous glaciation. Lakes Cootapatamba, Albina, Club, the Blue Lake and Hedley Tarn were formed during this epoch. Even this latest glacial epoch is divided into two, if not more stages.*"[137]

Professor David recognised that an older and larger glacial signature at Kosciuszko was produced by an ice-cap which carved the U-shaped valleys radiating N, S, E and W from Kosciuszko, prior to the more recent glacial activity associated with the lakes/relict cirques. David also reported scattered evidence of glacial debris far beyond the influence of the more recent cirque style glaciation, which produced the *Kosciuszko Moraines*. These evidences have been noted and included on the Kosciuszko Glacial Debris Map, (figure 8.1) as red dots, in chapter 8.

What evidence is there to support David's model for an Ice-Field over Kosciuszko which may have fed valley glaciers radiating outwards from Kosciuszko?

The main line of evidence is the discovery of glacial erratics and in 1908 David reported: "*numerous large blocks of phyllite were found by us in Spencers Creek valley, resting there on a granite surface*". He went on to say that "*These phyllite blocks must have been transported from the direction of the belt extending from Kosciusko to Mt. Twynam, a distance of 4 or 5 miles*". David also concluded that glacial ice "*forced its way over the high ridge of Charlotte's Pass, and having streamed down into Spencer's Creek … gouged out deep lake-hollows; on the eastern side of the Pass*".[138]

In his model, David has clearly separated the evidence for relatively recent, cirque-style glaciation coupled to lakes Cootapatamba, Albina, Club, Blue Lake and Hedley Tarn, from the older evidence, for possible large-scale Ice-Field glaciation. The same however, cannot be said for R. W. Galloway's (1963) model of Kosciuszko Glaciation. In Galloway's figure 6, (reproduced here as figure 7.2) he has combined the restricted cirque-style glaciation with a set of confluent valley glaciers, all of which he concluded, belonged to the most recent or "Wurm" glacial episode.[139] This model is a fiction. Tim Barrows (2001), mapped and dated only 15 km² of moraines and associated cirques, as corresponding to the most recent glaciation. Barrows however could find "*no well-preserved evidence of older or more extensive glacial events*",[140] at Kosciuszko.

In his 1963 reappraisal, Galloway relied on two premises, in order to disenfranchise all prior evidence of glacial erratics associated with a possible prior ice-cap. Firstly, he suggests that ***xenoliths*** (or fragments of Ordovician bedrock that have only been partly digested and homogenised by the intruding molten granite magma, and which have subsequently survived weathering of the enclosing granite), "***can be mistaken for erratics***" from the original Ordovician bedrock (unit ***Of***) which outcrops as a narrow band along the eastern flanks of the Kosciuszko Main Range.[141] Is this sufficient justification to deny all prior evidence of glacial erratics in the upper Snowy River?

Erratic fragments of these metamorphic rocks, (unit ***Of***) that have been carried southeastwards from the Kosciuszko Main Range by a possible prior Ice-Sheet, have been used to define its footprint. Galloway suggested that earlier researchers had confused these metamorphic erratics with surviving xenoliths, lying on granitic terrain southeast of the Main Range, or that larger chunks of metamorphic rock may occur randomly throughout the intruding granite and be mistaken for glacial erratics. If that were the case then it would be difficult to validate these metamorphic blocks as erratics and also make the inference that these lumps of metamorphic rock had been carried south-eastwards from the Main Range, and subsequently dumped onto the floor of Spencers Creek valley.

However, there are significant differences between xenoliths and the metamorphic rocks of unit ***Of***. These differences include a change in texture from the fine grained Ordovician metamorphic rock (of unit ***Of***), to medium-coarse grained xenoliths, due to their slow recrystallisation when trapped within the hot granite magma. Refer to the *Kosciuszko Photoglossary* for more information on xenoliths. Also,

the Kosciuszko area has been mapped by the Bureau of Mineral Resources in 1990 and no further outcrops or outliers of metamorphic rock have been noted in this area other than the one mapped by T. W. E. David in 1901, near Muellers Peak.

Galloway's second premise; that "***striations or faceting of the stones are not reliable indications of a glacial erosion***",[142] is contrary to over two hundred years of glacial research. Striae, polishing and faceting of debris entrained at the base of a glacier, are common characteristics and are endemic to the resulting sub-glacial deposits.[143] However, they are only well-preserved in hard, fine grained rock-types like quartzite. These diagnostic features rarely survive in granitic rocks. Both these premises used by Galloway are generalisations unsupported by specific field evidence, and they have allowed Galloway to sweep away any evidence that is inconvenient to his model.

Evidence dismissed by Galloway in his 1963 reappraisal included most of the erratics reported by Edgeworth David (1901) and (1908) as well as Browne and Vallance (1957, 1963) who reported ice scratched quartzite stones in the catchment of Spencers Creek.[144] Spencers Creek catchment is significant because it is beyond the influence of the late Pleistocene cirques and snow-fences that produced the *Kosciuszko Moraines* of the Last Glacial Maximum. One of the erratics found by David in lower Spencers Creek in 1908, may be the example illustrated in figure 11.1 below.[145] These large smoothed, rounded and striated blocks of fine grained phyllite, bear no resemblance to xenoliths found in the Kosciuszko region. The quartzite block found embedded within water-worn debris on the feature known as David's moraine [Spencers Creek Valley] and illustrated in figures 11.3 and 11.4 is totally consistent with glacially abraded debris.

In addition to general smoothing of rock surfaces; David noted U shaped valleys, hanging valleys and filled-up lake-basins as the chief evidences to be relied upon for the former extent of maximum glaciation.[146] T. W. E. David (1908) observed a hanging valley (at GR200657) in Wrights Creek,[147] which is a tributary of Spencers Creek and is illustrated in figure 9.14, (chapter 9) and marked on figure 11.2. Figure 11.2 below, is an oblique satellite image which portrays the position of evidence and landscape elements in Spencers Creek.

Galloway (1963) dismissed evidence in relation to erratics reported by: David (1901, 1908); Browne and Vallance (1957,1963) including ice scratched quartzite stones at 6150 feet (1870m) on the western face of upper Spencers Creek; in the David moraine, and also up along the valley flat of Trapyard Creek.[148]

Ongoing investigations by this author (table 1) below, have confirmed the evidence recorded by David and also by Browne and Vallance.

Figure 11.1 **Large metasediment erratic in lower Spencers Creek, GR 211702, about 1800mm long**
The bedrock in Spencers Creek is Mowamba granodiorite, referred to as granite by T. W. E. David. *"Numerous large blocks of phyllite were found by us in Spencers Creek valley, resting there on a granite surface. These phyllite blocks must have been transported from the direction of the belt extending from Kosciusko to Mt Twynam, a distance of 4 or 5 miles."* This rock specimen bears no similarities to xenoliths in this region.

Figure 11.2 **This satellite image looks NE and depicts an oblique view over the Snowy River**, **Guthrie Ridge and the catchment of Spencers Creek with locations of critical evidence**. Satellite image downloaded from Google Earth on 29th Sept 2019, © 2019 CNES/Airbus.

Table 1: Glacial Erratics in Spencers Creek Catchment

GRID REFERENCE	ALTITUDE	LOCATION/INTERPRETATION	NATURE of CLASTS
0619252E 5967462N	1860m	Stone layer below topsoil	100mm, sub-rounded, faceted block of quartzite with striations
203678	1860m	Clasts weathered out of stone-banked terrace below the saddle/col	Many cobbles: smooth to sub-rounded comprising hornfelsic schist, quartzite, as well as xenoliths. Provenance: 90% *ggb11*, 10% *Of*
NA	1740m	Till exposures along lower Trapyard Creek	Sub-rounded and polished cobbles and blocks of granite, quartzite, and quartz. Provenance: 65% *ggb11*, 35% quartz, 5% *Of*. Several quartzite blocks were faceted and striated.

The following figures further demonstrate that ice had probably flowed over the top of Charlotte Pass and continued down Spencers Creek Valley, and includes figures 11.3-11.5 below, which illustrate the striated and faceted block of quartzite which was found embedded in surficial debris on the lee side of the David Moraine and also the large quartzite erratic in upper Trapyard Creek.

In the centre of Spencers Creek Valley at GR 212674 is a smoothed bedrock outcrop of Mowamba granodiorite occupying about 25 ha. It has a discontinuous veneer of debris and is referred to as the David Moraine and is illustrated in figure 11.2 (above). The David Moraine feature has about 30m of vertical relief relative to the valley floor with the smooth sculpted form consistent with a *roche moutonnée*. (Refer to *Kosciuszko Photoglossary*). The provenance of the exposures of sub-rounded, smoothed and faceted blocks found around the margins of this feature are similar to the exposures at Johnnies Plain, being 65% granitic, about 5% metasediment (unit ***Of***), (mainly hornfels and quartzite) and 30% quartz and of course a small proportion of xenoliths weathered out of the surrounding granite.

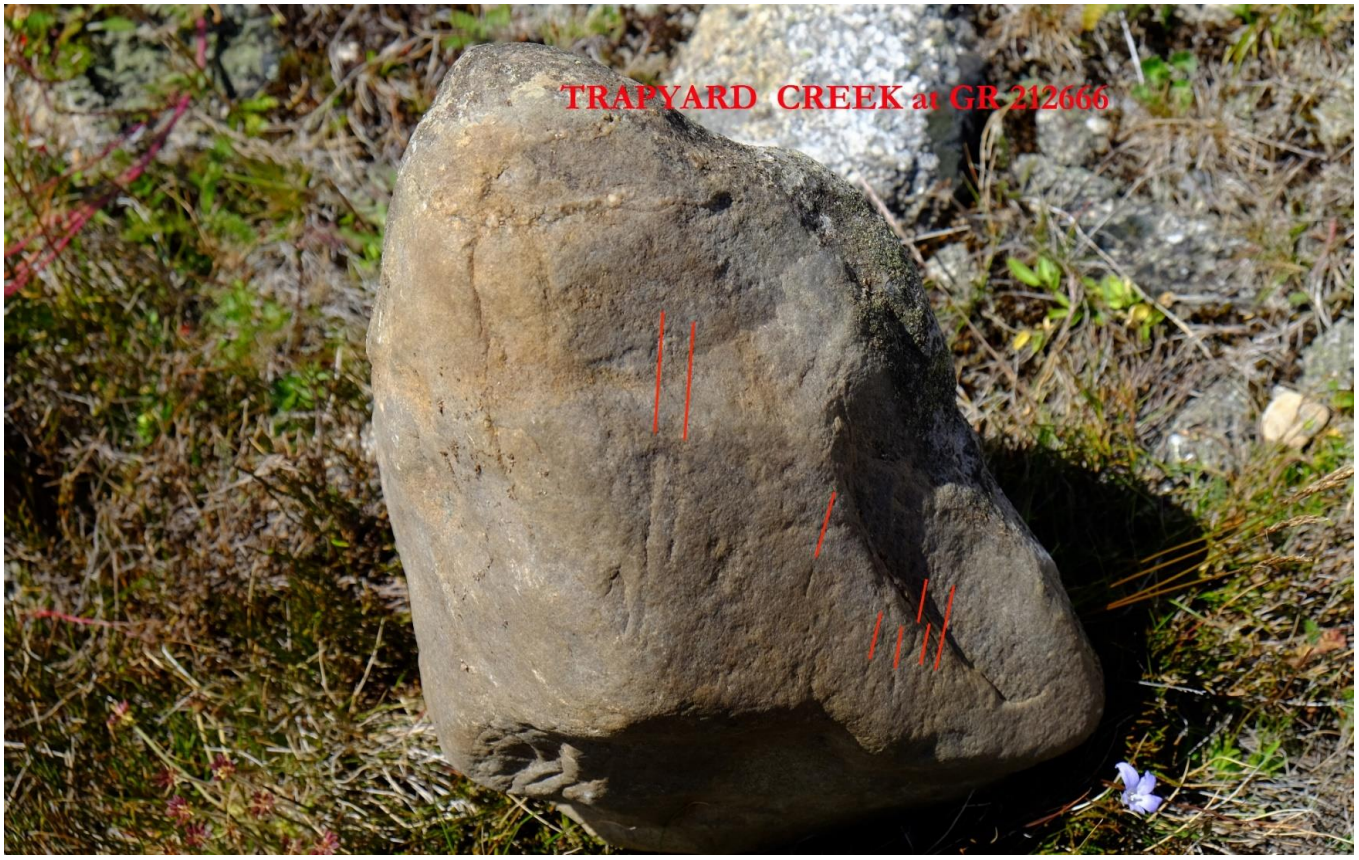
One erratic block found embedded at GR 0621497E 5967697N, and illustrated in figures 11.3 & 11.4 exhibits multiple sets of striations on its faceted faces. It has seven facets with multiple sets of striae within each facet and is very similar to the examples illustrated in plates viii and ix of David et al (1901). Figure 11.3 shows this specimen in situ within gravelly regolith on the David Moraine and figure 11.4 shows its underside. These surface features are unique indicators for glacial abrasion and have been well understood since the early observations of Louis Agassiz. A block with such marks and a provenance belonging to the metamorphic band of rock Unit ***Of***, which outcrop about 5km to the west; strongly supports the model for the overflow of glacial ice from the Snowy Valley via Charlotte Pass and or the saddle (possible Col) in the Guthrie Range at GR203678 at an elevation of 1870m.

Galloway's arguments against the validity of provenance and also of the validity of striae and faceting for erratics reported by prior workers in the catchment of Spencers Creek, are unsupported by the Geology of Kosciusko Map, (1990) and also by 120 years of geological investigation in this region. Galloway never located any random inclusions of metamorphic bedrock within the Mowamba granodiorite that makes up the Guthrie Range, and no one else has found metamorphic rock outcrop on the Guthrie Range that could act as a potential source for the quartzite cobbles and blocks, found in the catchment of Spencers Creek, let alone explain their polished and striated surfaces.

Figure 11.3 **This block of quartzite is photographed insitu at GPS GR:0621497E/5967697N.**

Figure 11.4 **This is the reverse side of the quartzite erratic at GPS GR: 0621497E/ 5967697N**.
This face is one of 7 facets on this block which is about 300mm diameter. Note the multiple sets of striations as well as 2 large and rounded crescentic gouges. These striations are distinct from *slickensides* which are usually unidirectional, flaky in nature and rarely preserved at the earth's surface.

Figure 11.5 **This large block of quartzite in upper Trapyard Creek** GPS GR:0621212E/ 5966596N or GR 212666 has a diameter of 500mm. It is sub-rounded, faceted and bears multiple, parallel striations. It is also a long way from home and has no resemblance to local xenoliths, which occur nearby.



What evidence do we have of remnant glacial debris and associated landforms in the Snowy Valley, upstream of Charlotte Pass?

David et al 1901, reported "*Tumbled quartzite blocks*" just NE of the Etheridge Ridge and underlain by granite, on his plate (iii), (figure 7.1).[149] The broad, gently rounded and smoothed feature (interfluve) beneath these large blocks is composed of Etheridge Adamellite (unit ***gab21***) and it separates the two converging branches of the Snowy River near GR 155658. These erratics are shown as red dots on figure 8.1 in chapter 8. These quartzite blocks are erratics but they are not part of a moraine (ridge), nor are they associated with a nearby cirque. The following image, figure 11.6 gives some context to this smoothed interfluve, underlain by Etheridge Adamellite, which is covered in a veneer of granitic and metamorphic glacial debris. Several prior researchers, including R. W. Galloway have mis-mapped the bedrock underlying this interfluve and have assumed it was an easterly bulge in the metamorphic rock of unit ***Of,***[150] but the bedrock boundaries represented on figure 8.1 (chapter 8) have been checked in this area, and are also consistent with the *strike* and *foliation* of unit ***Of*** along its eastern boundary. The disposition of the "tumbled quartzite blocks" reported by David (1901) are not consistent with the strike or dip of unit ***Of*** in this area as these blocks are not insitu.

Barrows et al 2001, presented a map of the glacial debris forming a veneer on part of this interfluve as well as along the Snowy Valley just upstream of here in their figure 2, as glacial moraine belonging to the last glacial maximum, (LGM). They have not realised that this apron of debris (mapped on their figure 2) which is of mixed granitic/metamorphic provenance on the valley floor and centred at GR153660, is not a moraine, nor is it consistent with the context of the *Kosciuszko Moraines*. This veneer of debris is *glacial till* and it and the underlying *roches moutonnées* on the valley floor are associated with an earlier, large-scale valley glacier.

Barrows' mentor, R. W. Galloway, stated that if the Snowy Valley glacier had been powerful "*there should have been extensive eastward transport of gneissic granite onto the metasediments and of metasediments onto the granodiorite*".[151] Galloway used his failure to find evidence of eastward transport of glacial debris to justify his conclusion that the Snowy Valley did not undergo effective glaciation. Both, the glacial till smeared across the interfluve above, (centred on GR 155658) covering at least 20 Ha; and also the granitic debris scattered across and downstream of the smoothed metamorphic bedrock ridge (roche moutonnée) centred on GR 144662; contradict Galloway's assumption and were not observed nor reported by Galloway in 1963.

All the erosional and depositional evidence of the LGM at Kosciuszko as well as the associated palaeoclimatic evidence, support a very restricted glaciation constrained by aridity during the LGM, which is totally inconsistent with a large valley glacier at this time and place. If the glacial debris mapped by Barrows et al (2001) was debris resulting from cirque-like glaciation moving off the adjacent Mt Clarke, it would have a strictly metamorphic provenance from the underlying bedrock of Mt Clarke and the terrain just east of Mt Clarke. Clearly, this is not the case.

Figure 11.6 **View northeastwards down the Snowy River Valley from a position near Seamans Hut.** The central dashed line marks the contact between the metamorphic bedrock of unit ***Of*** to the left of view, and the granitic bedrock of unit ***gab21*** to the right of view. The smoothed, gently rounded interfluve (to the right of view) referred to above, appears to be a roche moutonnée and is labelled as such. In addition, there are two smaller roches moutonnées to the left of view. These landforms are discussed in the *Kosciuszko Photoglossary* and they represent glacially abraded bedrock, shaved by glacial ice, over-riding the bedrock in the floor of the valley. The entire surface of this interfluve/roche moutonnée is plastered with glacially abraded debris of both granitic and metamorphic provenance. These roches moutonnées and the smooth veneer of glacial debris covering them, are consistent with a large-scale valley glacier having ploughed down the Snowy Valley prior to the LGM. Note the outcrops of ***gab21*** marked on the figure below.

Now consider the Snowy Valley adjacent to Charlotte Pass

Figure 11.7 **Glacial debris in the floor of the Snowy Valley**

This figure looks eastwards towards Charlotte Pass. There are three dissected terraces in the floor of the Snowy Valley and a large 4m erratic of hornfels (unit ***Of***) in the foreground, above and west of the terraces. The bedrock in the valley floor is Mowamba Granodiorite. The nature of the debris in these terraces is shown below.

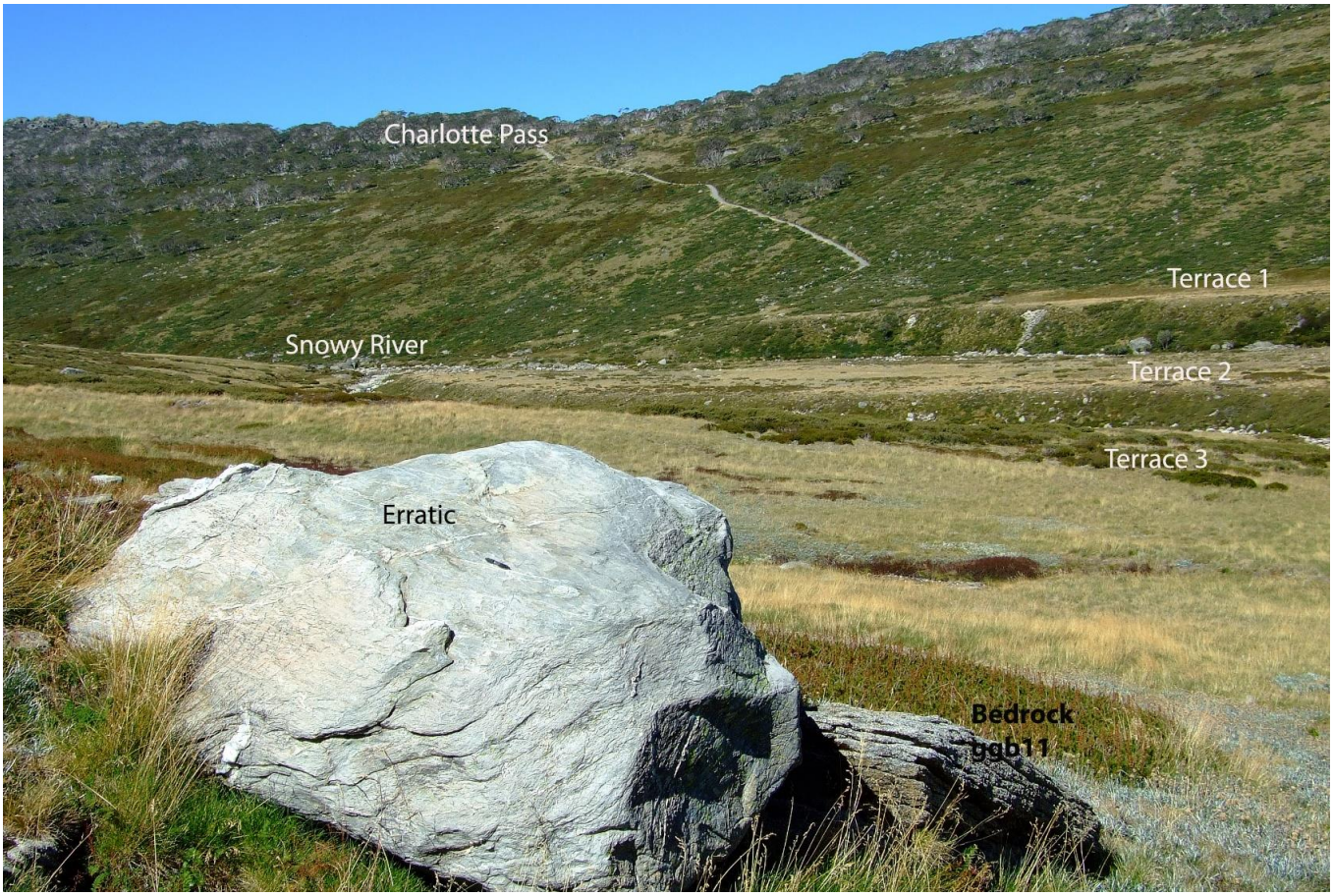


Figure 11.8 **Closer view of erosion scar in terrace 1 of fig 11.7**
This exposure in the side of terrace 1 reveals 8m of unconsolidated blocky debris of granitic and metamorphic provenance. There is no organized bedding structure within this debris. This terrace is a dissected remnant of a prior, much broader sheet of debris which has been eroded by the Snowy River. In 1901, professor David reported "*Ice striated boulders*" near here on his plate (iii). A close-up view follows in figure 11.9.

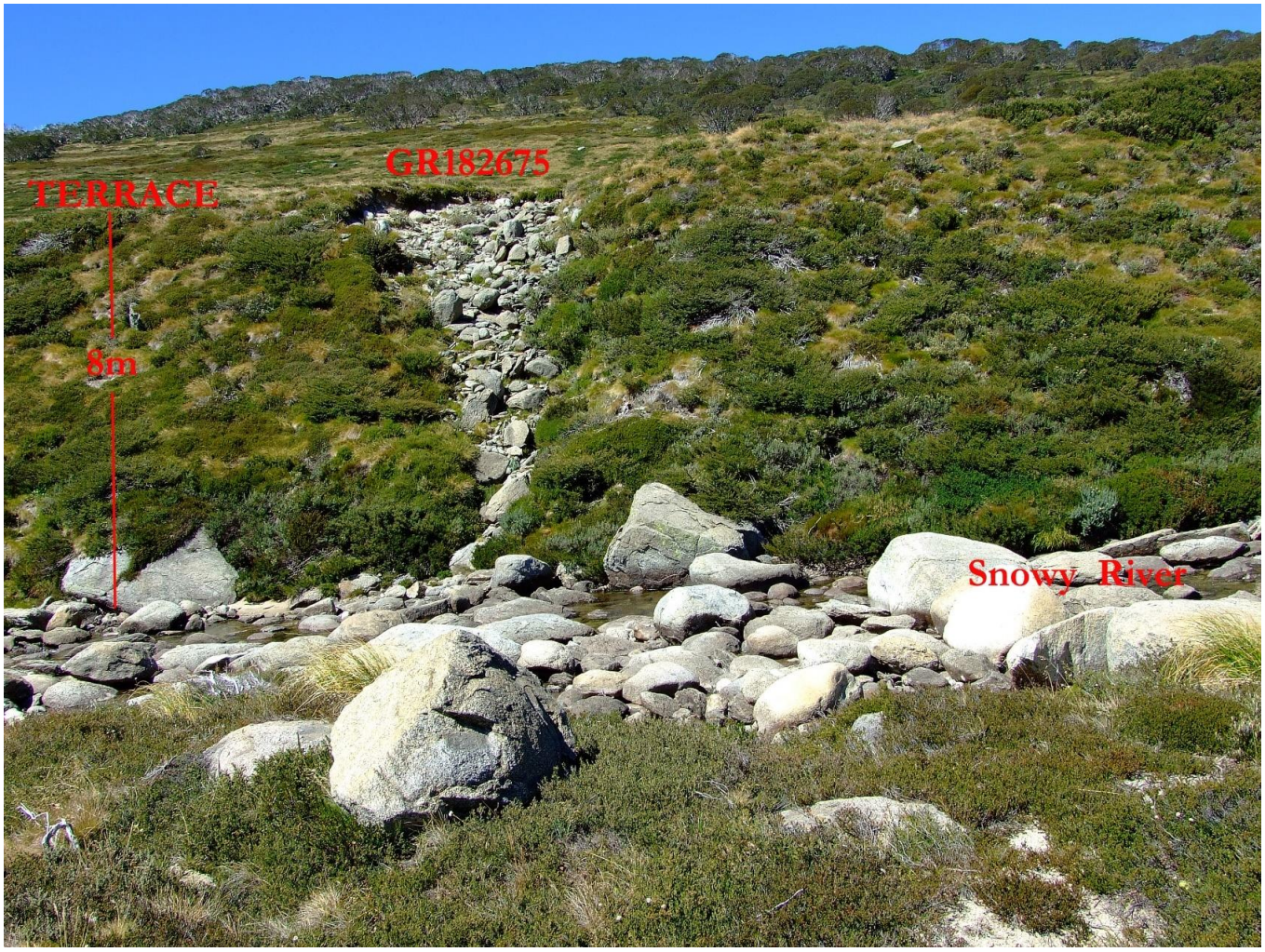


Figure 11.9 **Close-up of exposure in terrace 1**.

This figure shows that the bouldery debris is infilled with a matrix of sand, gravel and cobbles, some of which are pale grey, fine grained metamorphic rock of unit ***Of.*** This massive, unstratified debris is not typical of riverine deposits but is very typical of glacial debris. Also note the parallel striations in the quartzite block at lower right which further suggests glacial debris. The following map presents evidence of surficial debris and glacial abrasion of this local landscape of the Snowy Valley adjacent to Charlotte Pass.

Figure 11.10 **Geomorphology and glacial debris associated with the terraces in the floor of the Snowy River Valley**.
Red= outer moraine from Mawson Cirque (LGM).
Yellow=abraded and sculpted bedrock including TS(Truncated Spur), C(Col) and AI(Abraded Interfluve).
Purple=Glacial debris with metamorphic provenance carried from the NW.

Due to the good vegetation cover, these outcrops of glacial debris appear very patchy, but they continue across the spur north of the terraces towards the NE and contain polished, faceted and striated blocks of quartzite and hornfels from unit ***Of.*** It is fairly evident that the massive deposit of glacial debris in the floor of the valley (dissected terraces), the veneer of glacial debris across the adjacent spur and the truncated spurs and ground down interfluve, are all consistent with a large valley glacier passing over this terrain. Notice how the 1800m contour on the eastern side of Charlotte Pass has a re-entrant curve right at the Col, which is independent of any marked drainage line and as this contour line tracks eastwards, both arms north and south of upper Spencers Creek run parallel for about 800m consistent with ice abrasion caused by an ice-stream overtopping Charlotte Pass. Supporting the geomorphic observations in figure 11.10, are the following cross-sections across the Snowy River and Spencers Creek, which are not typical of the normal V shaped river profile evident further downstream.

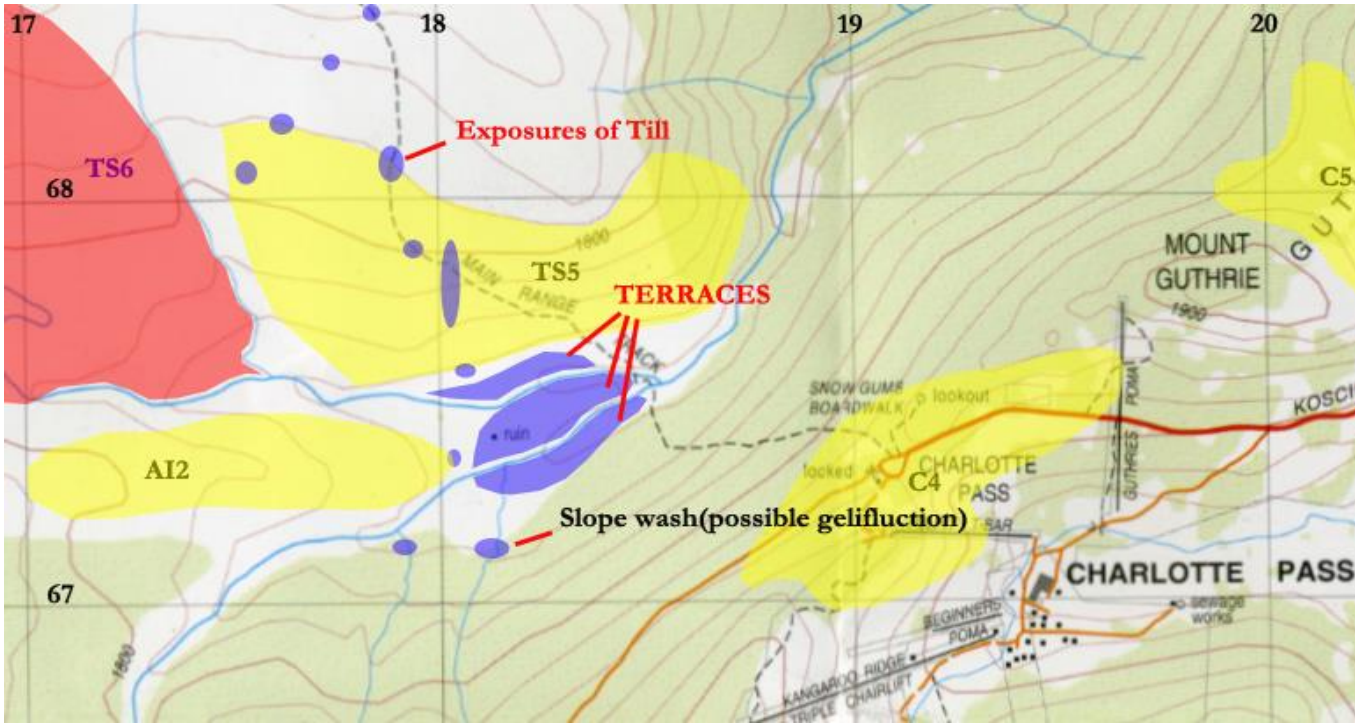


Figure 11.11 This section shows a U-shaped valley with a flattened spur on the northern flank below Mt Clarke and an incised col on the southern flank near Seamans Hut at 2020m. A moraine about 300m-400m south of Seamans Hut also suggests that ice filled the Snowy Valley and spilled over the col near the hut.

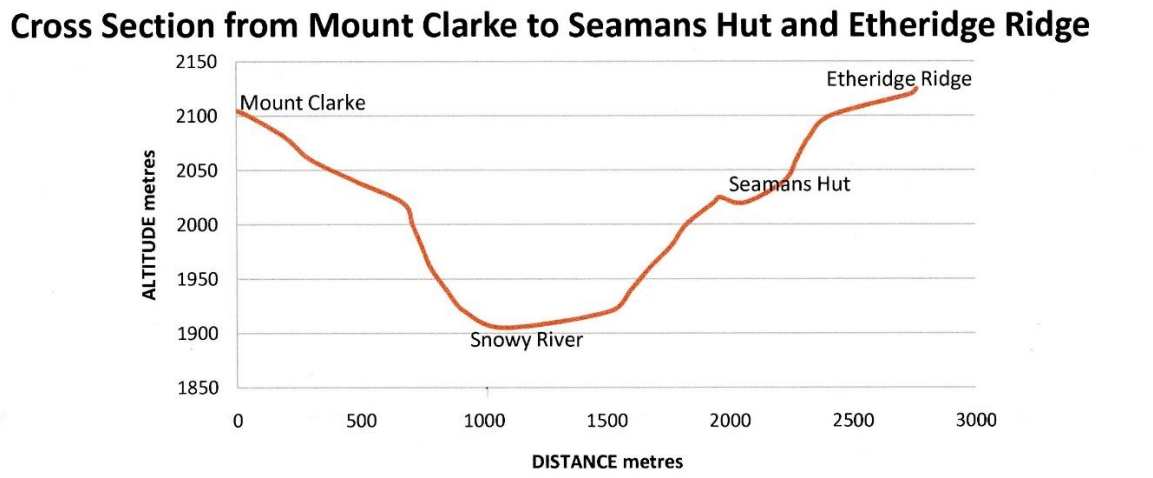
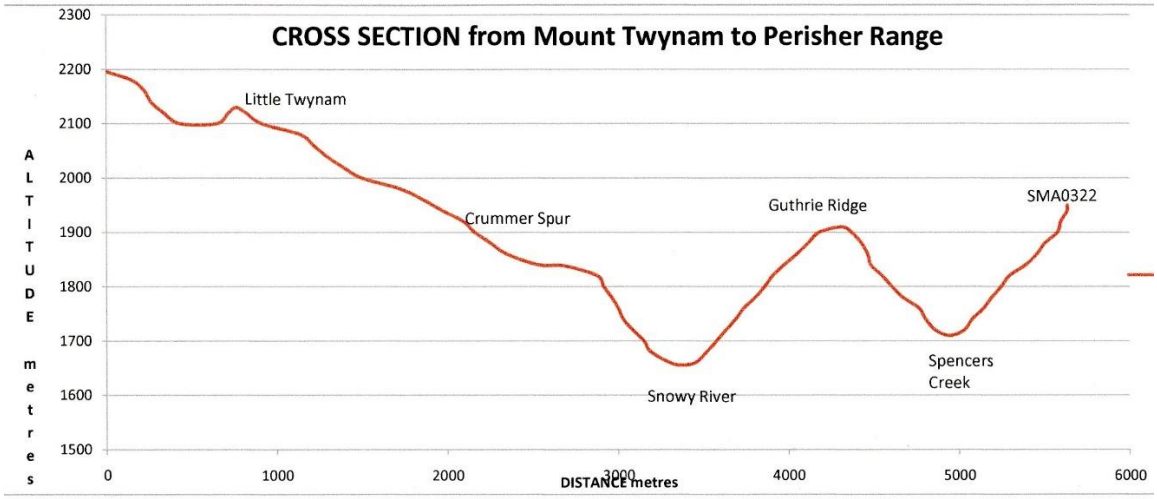


Figure 11.12 This section which traverses two valleys, displays valleys with two sets of catenary curves, with the lower curve inset into the upper. The NW shoulder of the Snowy Valley has been ground down between 1820m and 1900m by ice moving southeast from the Blue Lake Glacier which has then joined the Snowy Glacier and continued to truncate all the descending spurs for the next 4km. Spencers Creek has the same profile pattern as the Snowy River and rejoins it 2km downstream from here.



How far might this prior valley glacier have travelled?

Figure 11.13, **looks northeastwards down the Snowy River Valley from a point above Charlotte Pass**. The U-shaped profile continues NE as far as Guthega. There are remnants of glacial debris just upstream of Guthega and just upstream of the junction of Spencers Ck with the Snowy River as shown on the next map, figure 11.14.
Satellite image downloaded from Google Earth on 12th May 2020. Image ©2020 CNES/Airbus.

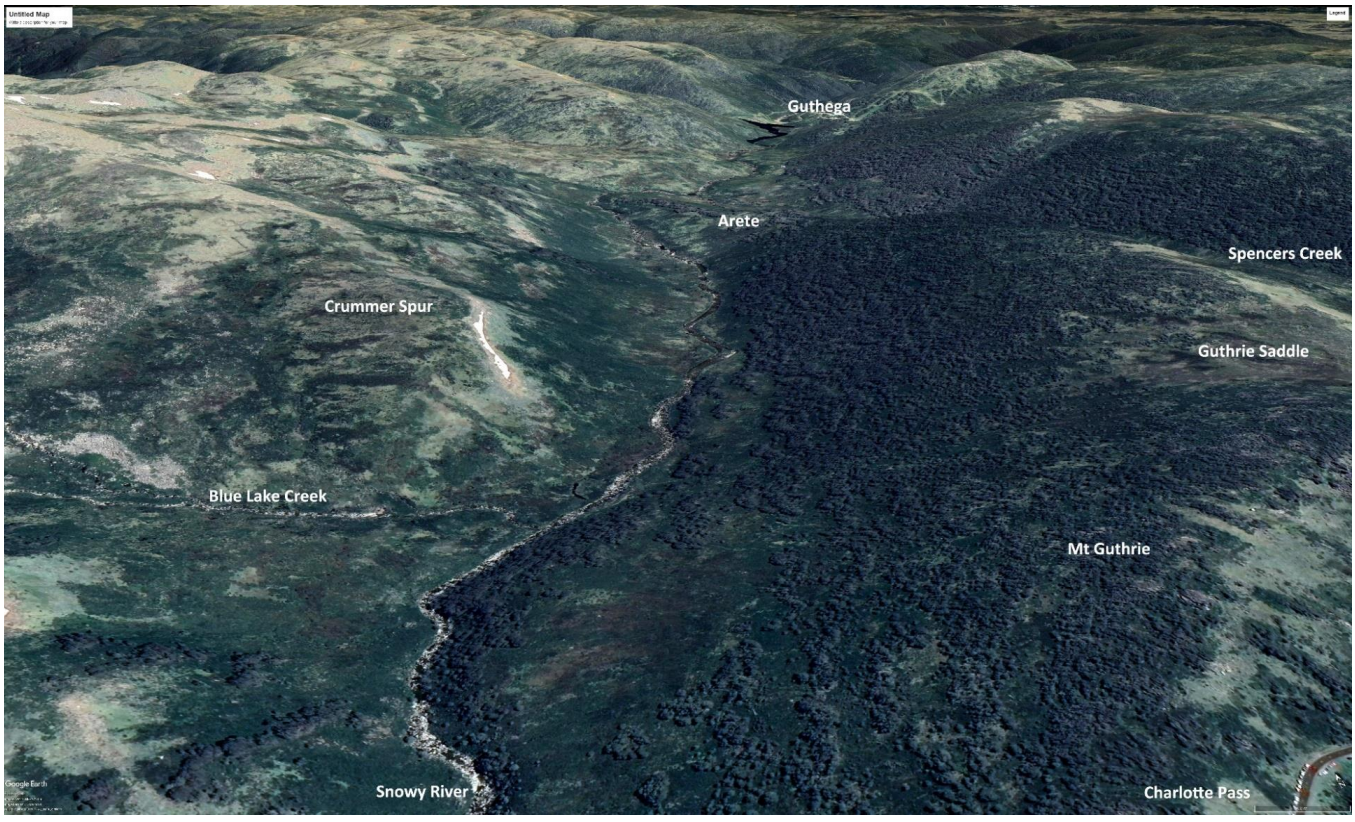


Figure 11.14. **Glacial Features Map, Snowy Valley and Spencers Creek.**
Red= Late Pleistocene *Kosciuszko Moraines*.
Yellow= Glacially abraded terrain: TS truncated spurs; RM roches moutonnées; AI abraded interfluves; C cols; FS flattened spurs.
Orange= glacially abraded terrain with traces of fluvial debris.
Blue=Glacial debris which predates the *Kosciuszko Moraines*.
Basemap extracted from Perisher Valley 8525-2S, 1:25,000 topographic map ©2001 Department of Lands, NSW Government.

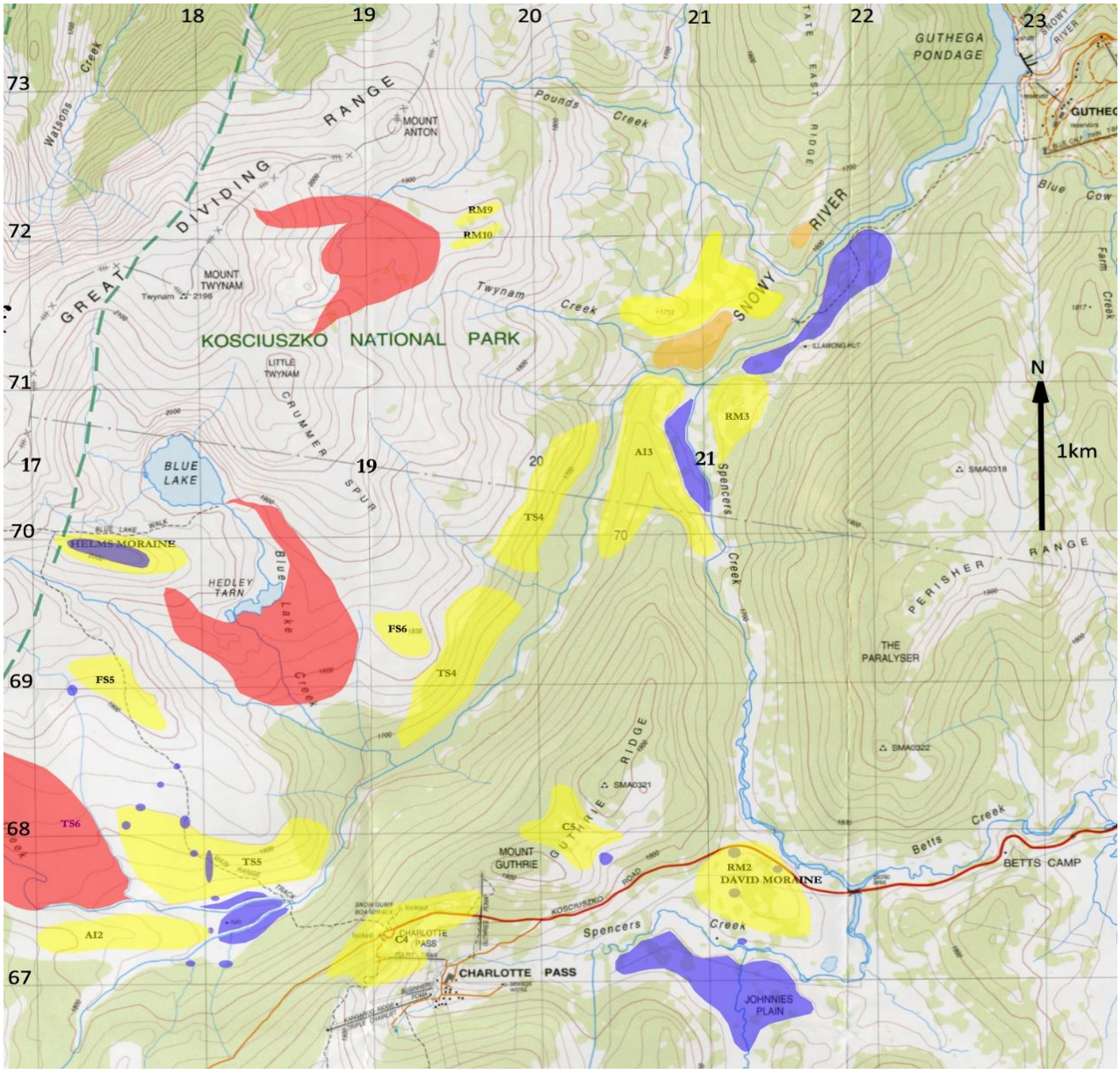


Figure 11.14 collates evidence of older glacial debris (blue overlay), which predates the *Kosciuszko Moraines* (red overlay) which are associated with the cirque-style glaciation of the late Pleistocene. These older patches of debris are mostly glacial till and they form

discontinuous exposures of well vegetated, coarse glacial debris smeared onto the landscape. These fragments of evidence have been classified as glacial on the basis of rounding, faceting and striation of individual blocks of metamorphic rock, and also on the overall poorly sorted fabric of the residual sediment which comprises boulders, cobbles, gravel, sand and silt of mixed provenance. The descriptors for such a classification can be found in references such as Benn and Evans, (2010).[152]

Figure 11.14 shows glacially abraded terrain with a yellow overlay. The truncated spurs are characterised by relatively straight parallel contours in zones where they would normally be convex outwards. Abraded interfluves are either ground down with a very gentle slope like AI-2 at the junction of Club Lake Ck with the Snowy River or they have a very acute bend in one or more contours like the 1700m contour at AI-3, caused by lateral abrasion by ice against the Guthrie Ridge near the confluence of the Snowy River with Spencers Ck.

The till covering Johnnies Plain on the southeastern flank of Spencers Ck may be a remnant terminal moraine of David's older, ice-field glacial episode. It pinches out rapidly to the south, and there have been no blocks of metamorphic provenance observed beyond the mapped area to the immediate south.

To the north, the blocky debris on the western flank of Spencers Ck just prior to its intersection with the Snowy River, may be a *recessional moraine* deposited during the decline and retreat of valley glaciation.

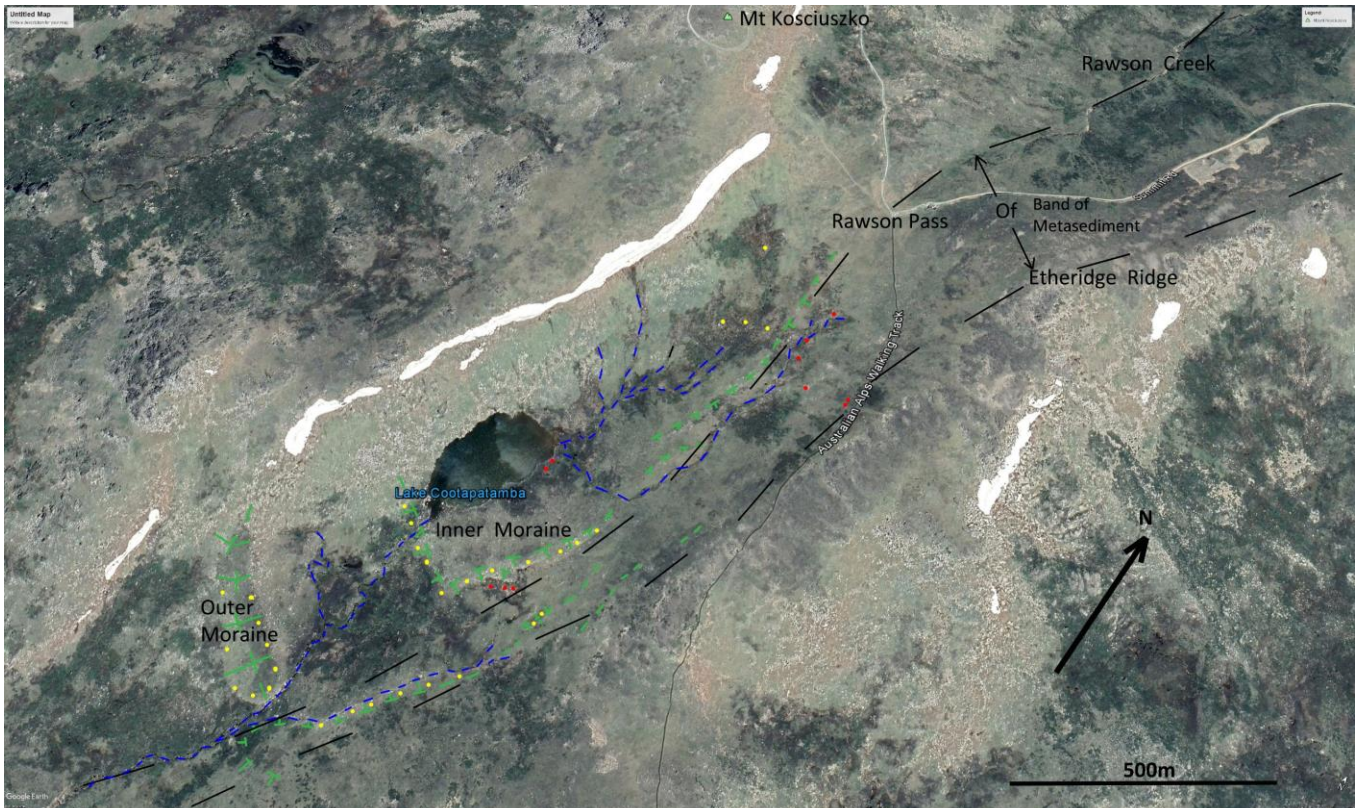
Further down the Snowy Valley near Illawong Hut are exposures of slightly elevated unconsolidated debris, sitting on fragments of bedrock dissected by erosion and downcutting by the Snowy River, during subsequent interglacials. It is possible that this valley glacier terminated near Guthega, but this is unresolved. The terraces in the floor of the Snowy Valley below Charlotte Pass were probably also *recessional terminal moraines* related to a prior valley glacier which was fed by an ice-field over the Kosciuszko Main Range.

Moderately large *roches moutonnées* are common throughout this glaciated landscape and are indicative of relatively shallow ice thickness and hard bedrock, under a temperate-style valley- glacier.[153] Roches moutonnées are discussed and illustrated in the *Kosciuszko Photoglossary*. This evidence in the Snowy Valley is consistent with a modest valley glacier moving northeastwards from Kosciuszko towards Guthega and overflowing Charlotte Pass where it combined with ice accumulating in Spencers Creek catchment which continued northwards to rejoin the Snowy Valley Glacier. There would need to have been a source for all this ice flowing northeastwards from Kosciuszko.

The only logical solution would be an Ice-Field above the Kosciuszko Main Range and the limited surface area of the Kosciuszko Main Range would also have limited the extent and erosive power of any valley glaciers which may have acted on this landscape during the Pleistocene.

Now consider the U-shaped valley descending from the relict glacial col of Rawson Pass towards the small relict cirque known as Lake Cootapatamba, and beyond.

Figure 11.15 **Valley below Rawson Pass trending SSW.** Green form lines show moraine outer ramparts and ridges. Blue dashes are drainage lines. Yellow dots indicate granitic debris of unit ***glw7***. Red dots indicate metamorphic debris with provenance, unit ***Of***. Note that the long axis of the lake is about 250m. The metamorphic band of rocks (unit ***Of***) is shown by black dashed contact lines. West of this unit ***Of,*** is the granitic unit Rawson Pass Adamellite, (unit ***glw7***) which comprises the ridge SSW of Kosciuszko; and east of the band of metamorphic rocks is another granitic unit, Etheridge Adamellite, unit ***gab21***. North is shown in the lower right corner as is the approx. scale. Basemap is satellite image downloaded from Google Earth on 14/12/2019 ©2019 CNES/Airbus.



In 1901 David et al wrote: "*An examination of the valley which descends from Ramshead Pass* [Rawson Pass] *to the lake shows throughout ice smoothed surfaces and moraine material with occasional ice scratched blocks….Such few boulders as exhibit glacial markings are of feldspathic quartzite, and were derived from the east side of the valley….*".[154]

This observation is important because the paired inner and outer moraines adjacent to Lake Cootapatamba have a provenance that is >99% Rawson Pass Adamellite (unit ***glw7***) which has been derived from the SSW trending ridge from Kosciuszko. The bedrock underlying the catchment of this small cirque is entirely Rawson Pass Adamellite. There should be no metamorphic rock within the inner

moraine at Cootapatamba, as can be seen from David et al plate (iii) [figure 8.2] and also figure 11.15 above. This writer located numerous examples of faceted, polished and striated blocks of quartzite in the U-shaped trough above Lake Cootapatamba and only 200-400m south of Rawson Pass, shown as red dots on figure 11.15. These blocks in the floor of the valley are 20-50m higher than the highest part of the moraines adjacent to Lake Cootapatamba and their provenance is inconsistent with glacial debris eroded from the granitic rock which underlies the catchment of this small relict cirque glacier.

These sub-rounded, polished, faceted and striated blocks are not xenoliths as Galloway (1963) would have us believe. A discussion of xenoliths and common bedrock types can be found in the *Kosciuszko Photoglossary*. These striated blocks are probably associated with a prior valley glacier moving SSW down this valley from an ice-cap above Kosciuszko and the Main Range, before the late Pleistocene.

David et al (1901) also observed metamorphic blocks at the eastern edge of the inner moraine. They wrote: "*The best ice-scratched blocks obtained by us were at the base of the terminal moraine near its east end*".[155] This writer has located 5 more sites of metamorphic blocks close to or within the inner moraine at Cootapatamba. Three of these sites were at the eastern edge of the inner moraine wall and two were close to the lakes edge on its NE corner. Refer to figures 11.16-11.18. All of these sites are west of the contact with the metamorphic band of rocks as indicated on figure 11.15.

These erratic-blocks must have been sitting further to the northwest of their present positions prior to the last glaciation which would have dozed them southeastwards and subsequently incorporated them into these *Kosciuszko Moraines*. Some might query if there could have been a large xenolith or another band of metamorphic rock within the granitic backwall behind the lake. Xenoliths are quite distinctive from the fine grained quartzites as they usually have some medium to coarse grained crystals and a zoned texture. An examination of the backwall revealed only massive, coarse grained Rawson Pass Adamellite bedrock upslope of the lake.

The only satisfactory explanation given the evidence, is that these five metamorphic blocks had been eroded and transported towards Lake Cootapatamba by a valley glacier bearing down from the vicinity of Rawson Pass where they sat until reactivated by ice sliding off the flanks of the Kosciuszko South Ridge behind and NW of the lake during the LGM.

Some earlier researchers considered that the moraines associated with Lake Cootapatamba may have developed from a valley glacier moving directly down the valley towards the SSW. This scenario however, doesn't fit the orientation of the associated moraines. A valley glacier from the NNW, terminating near Lake Cootapatamba would have spread moraine in an arc at right angles to its direction of flow, and across the valley floor. These inner and outer moraines however, are very asymmetric with an elevated anchor point against the Kosciuszko South Ridge. They then thin and curve upstream forming a rapidly thinning ridge of debris running up and parallel to the centre-line of the valley. This is further illustrated in the *Kosciuszko Photoglossary*.

The only plausible explanation for the above abraded blocks of quartzite is that a valley glacier descended from an ice-field over the Kosciuszko Main Range which pushed SSW and carved the U-shaped trough which descends towards Lake Cootapatamba and beyond, at a time prior to the activity which generated the *Kosciuszko Moraines*.

Figures 11.16 to 11.18 below, illustrate glacially abraded blocks of metamorphic rock which were probably derived from the outcrops of unit (***Of)*** up near Rawson Pass, prior to their final displacement during the last glacial maximum.

Figure 11.16 **Quartzite block at GR 137641 and about 600m NNE of Lake Cootapatamba**. It bears two facets, the upper one also bearing polish and multiple sets of stria. There is a second set of faint striations along the upper edge aligned at about 40^{o} to the lineations marked in red

Figure **11.17 Quartzite block at GR138641 close to the walking track, and close to 2100m asl, and NNE of Lake Cootapatamba**. It shows a polished facet with two parallel gouges.

The feldspathic quartzite mentioned by David et al, is a common component of the band of metamorphic rock of unit ***Of***. The red dots marked on figure 10.15 represent blocks of quartzite sampled by this writer. The uppermost 6 samples all lie within the metamorphic bedrock zone but each of them exhibits glacial abrasion with one or more of the following features: sub-rounding, faceting, polish and striations/gouges. Figures 10.16 and 10.17, and 10.18 illustrate 3 of those 6 samples.

Figure 11.18 **This sub-angular block of moderately weathered quartzite with rounded edges was found at GR137643, NNE and upslope of Lake Cootapatamba**. This sample exhibits two sets of striations on the facet

The next question should be: How far did this prior valley glacier extend downstream?

Table 2: Depositional Evidence below Lake Cootapatamba

Feature	G.R. GDA94 Grid	Altitude metres	Area Hectares	Landform Association	Nature of Deposit	Bedrock	Provenance	Clast Morphology
Dissected Terraces	125625	1920-1940	25	Dissected Fan-shaped sheet of till in valley floor.	Glacial till of depth = 1.1 m.	glw7 Rawson Pass Adamellite	Granitic 80-90% Unit *Of* Metased 10-20%	Massive fabric of poorly sorted sub-angular to rounded cobbles and blocks of granite, quartz and hornfels and quartzite in a gravelly matrix. Some clasts are faceted and one clast at GR123624, had possible remnant striations. One quartz block (1.2mØ) on top of the terrace and well removed from the creek has well rounded edges and a smooth sculpted surface consistent with glacial abrasion.
Apron of Till	120620	1890-1910	25	Broad apron of mostly vegetated till across the floor of the valley.	Glacial or fluvioglacial till of unknown depth	glw7 Rawson Pass Adamellite	Granitic 50% Unit *Of* Metased 50%	Sub-rounded cobbles and blocks of granitic and metased in gravel matrix.

For some reason, no accounts have been reported of systematic exploration of this valley below Lake Cootapatamba. David notes that: "*A cursory examination of the rocks for a short distance below the level of this older terminal moraine showed that they were more or less smoothed, apparently by ice, for some distance down the valley. Definite evidence, however, of ice action was not observed below the lower moraine dam…*".[156]

The broad, smoothed U-shaped valley continues for another 2.5 km before it splits, with one branch continuing west down the Swampy Plain River and the other fork veering up over a gentle incline then down into the Leather Barrel Creek. What form of erosion is capable of flowing up and over terrain like this?

The evidence for this is shown where the reentrant in the 1900m contour near GR 118614 (figure 11.19 below) has been carved by ice as it pushed uphill across the southeast flank of the Swampy Plain River. The location of the reentrant is on a gentle slope dipping back northwestwards but the reentrant indicates erosion and ice- flow in the opposite direction. Depositional evidence is summarized in table (2) above.

The debris deposited in the large terrace between 1 and 2 km downstream of Lake Cootapatamba is consistent with glacially abraded debris as illustrated in the figures below (figures 11.19 to 11.23).

Figure 11.19 **Cootapatamba and environs: glacial features map**.
Both the inner and outer moraines hook up the centreline of the valley but they thin rapidly upslope. Note that the moraine terraces downstream of Lake Cootapatamba have a significant component of metamorphic debris but they are situated west of the metamorphic bedrock and are effectively upslope of the adjacent Swampy Plain River. These moraine terraces lack a potential fluvial transport mechanism. What does the fabric and clast morphology of these moraine terraces tell us about their likely genesis?

Basemap is extracted from Perisher Valley 8525-2S Topographic Map © 2001 Department of Lands, NSW Government.

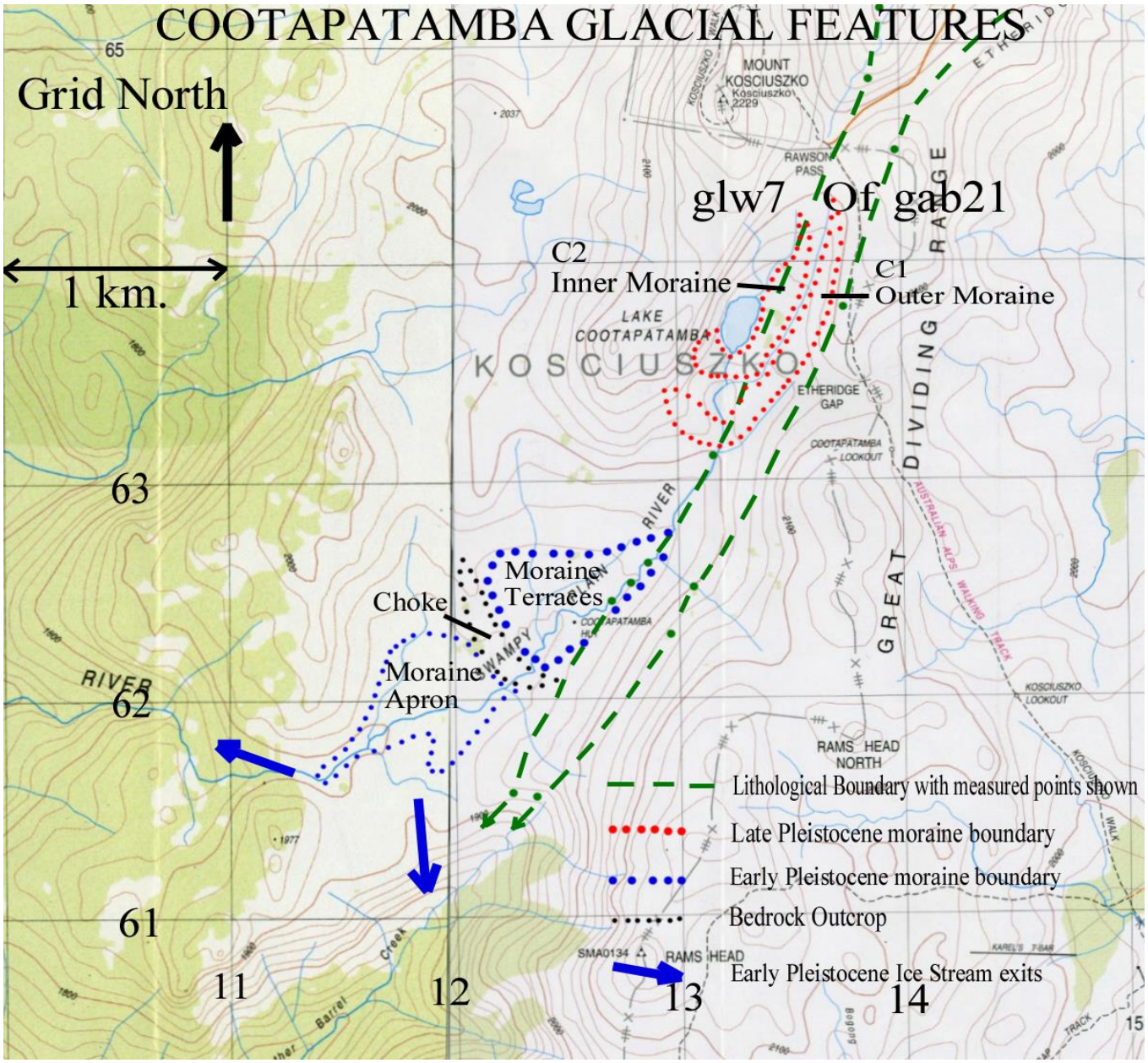


Figure 11.20 **Exposure of relict moraine at GR 612459E/5962315N.**
Some metamorphic cobbles and blocks of unit ***Of*** are labelled in fig 11.20. They constitute about 10% of this section. The blocks and cobbles are supported in a gravelly matrix, are poorly sorted and sub-angular to sub-rounded in shape. This fabric is consistent with glacial moraine.

Figure 11.21 **Exposure of moraine terrace in creek cutting at GR 124627**.
This site is well elevated and 300m NW of the Swampy Plain River. The supporting role of the gravelly matrix is clear to see especially to the left. Note the fine grained, rounded block within the matrix with a smoothed surface at centre left. It sits in contrast to the larger more angular granitic blocks. This poorly sorted sediment is not typical of fluvial sediment and the metamorphic blocks, could not have washed into this elevated location. It is quite similar to the 8m exposure in terrace 1 in the Snowy Valley below Charlotte Pass, figure 11.9.

Figure 11.22 **Lateral creek exposure 1.3 km downstream of Lake Cootapatamba and 200m NW of Cootapatamba Hut.**

This terrace section has a significant proportion of metamorphic blocks which show faceting, sub-rounding and occasional striations.

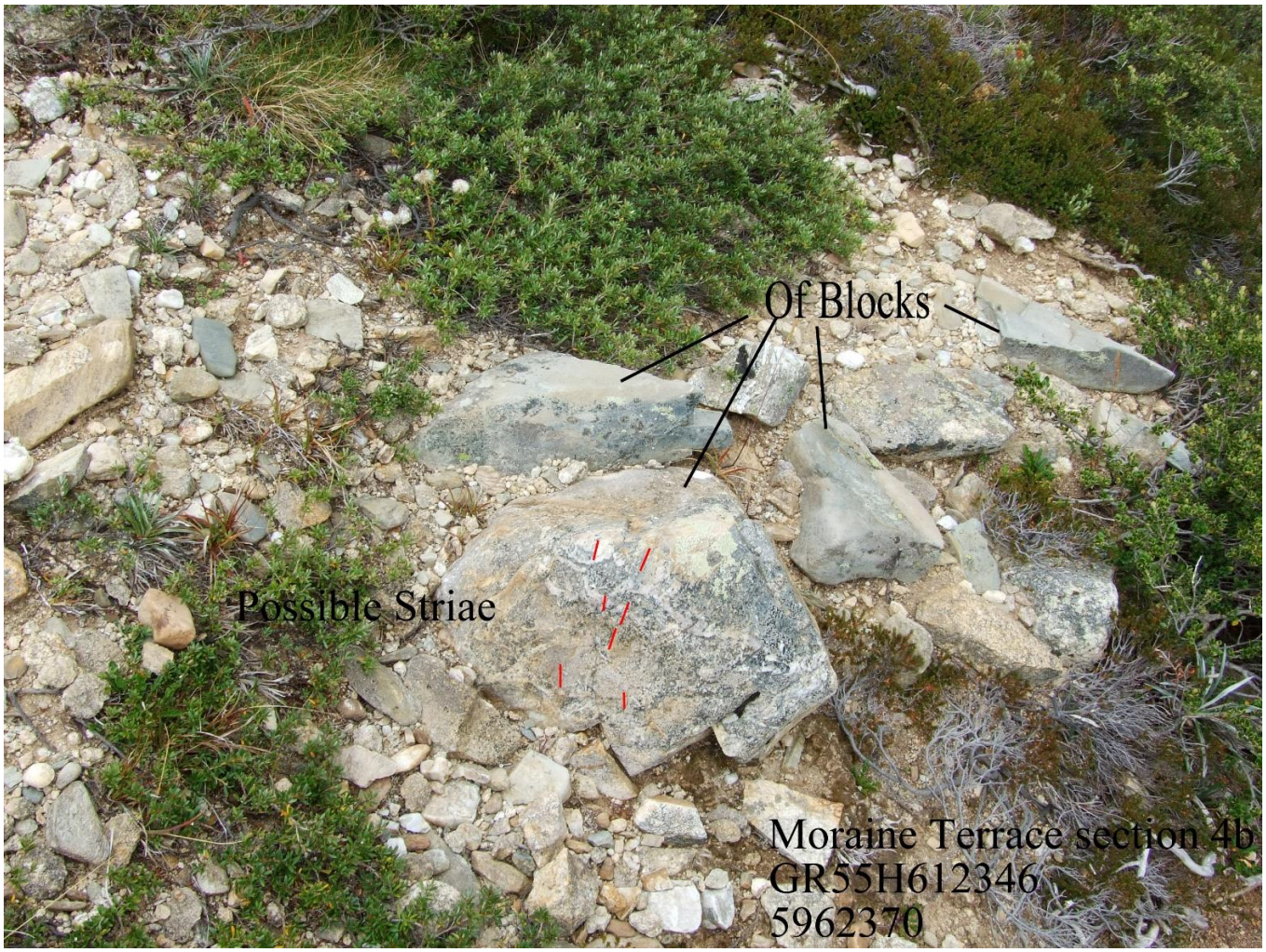
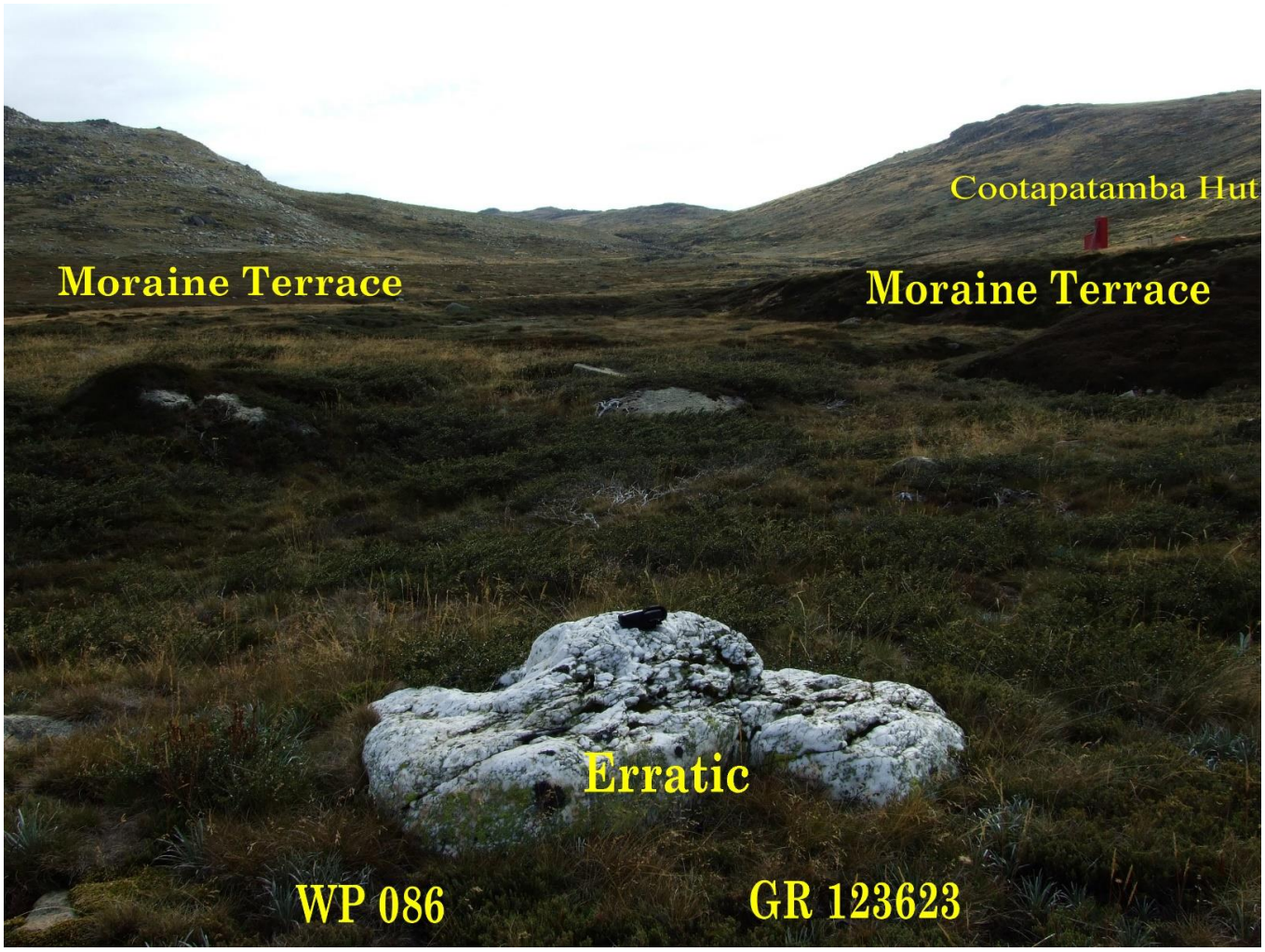


Figure 11.23 **Central position on moraine terraces, about 200m west of Cootapatamba Hut and 1.5 km downstream of the lake and looking upstream.**

This large sub-rounded and smoothed block of quartz (1200mm diam) sits on top of an extensive terrace (covering about 25 Ha). Its appearance is consistent with glacial abrasion. This terrace has been dissected by the upper reaches of the Swampy Plain River.
This view looks upslope and the Cootapatamba outer moraine appears as a barrier across the U-shaped valley of the upper Swampy Plains River in the background.



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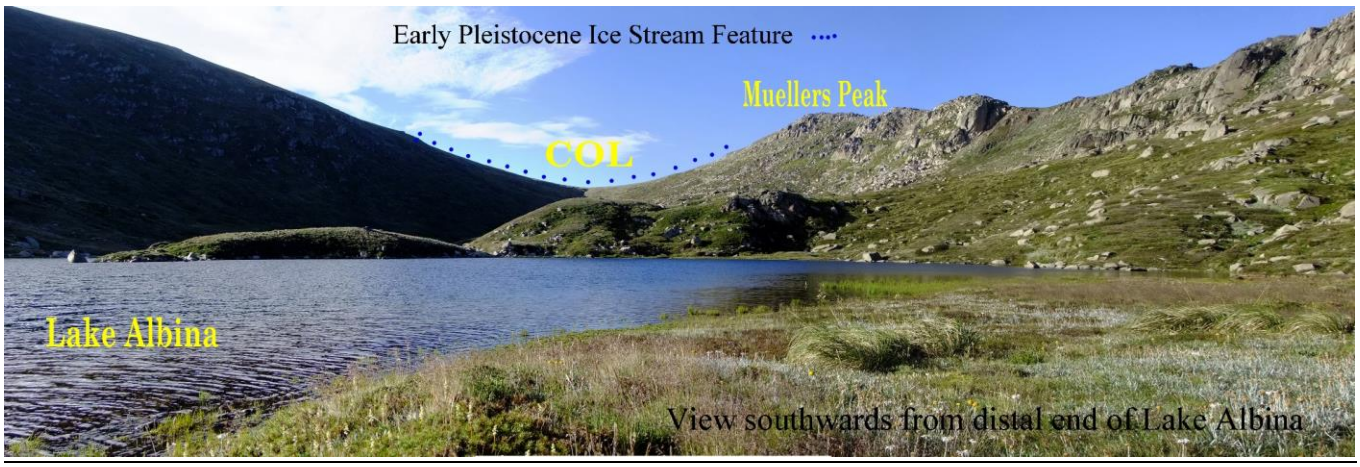
Now consider the valley running northwards from Albina Pass.

Figure 11.24 **This view looks southwards towards Albina Saddle from Lake Albina** and shows the inscribed glacial col at the head of the valley (marked with blue dots) and the smoothed bedrock forms of a set of roches moutonnées in the valley floor at centre of view.



The *Kosciuszko Moraines* adjacent to Lake Albina have already been described, (Ch 8). However, the curved abraded incision cut into the bedrock of this saddle cannot be explained by the actions of the cirque-like glacier that just managed to push the debris in the outer moraine only 500m beyond the lake, during the late Pleistocene.

Also, the tiny, cirque-like glaciation of the late Pleistocene moved in an easterly to northeasterly direction which is inconsistent with the orientation of the lake. What other evidence do we have?

In figure 11.25 below, the arrow north of the lake points towards a truncated spur possibly caused by glacial abrasion about 1km beyond the Lake Albina outlet. The arrow next to the roche moutonnée indicates probable direction of the ice stream down-valley. The X on the western valley flank in figure 11.25 marks approx. location of deeply inscribed gouges on a polished surface of granodiorite bedrock bearing 040^{o} MB. This gouge indicates relatively recent glacial abrasion which has moved debris to the NE towards the distal end of the outer moraine on the opposite side of the valley, where the provenance is dominantly granodiorite of unit ***ggb31***. We appear to have evidence of two types of glacial movement preserved in this valley with differing intensities and directions.

The roche moutonnée and the truncated spur 1km downstream as well as the U-shaped incision in the valley profile adjacent to the distal end of the lake (in figure 11.25) all point towards a large volume of ice having moved northwards directly downstream of Lake Albina, rather than across the valley, which

was the case during the late Pleistocene. Figure 11.25 also includes a smoothed, flattened spur (mid-ground at right of image), 500m NE of the distal end of Lake Albina which is also shown in figure 11.26 below.

Figure 11.25 **View northwards from the walking track behind Lake Albina.**

Figure 11.26 **View over flattened spur NW of Lake Albina and west of Mt Lee.**

The black arrows point at granitic erratics sitting on metamorphic bedrock. These were first reported by R.W. Galloway and Joe Jennings in 1972. This flattened spur composed of metamorphic rock (unit ***Of***), is interesting because, not only are there four erratics of Rawson Pass Adamellite (unit ***glw7***) sitting on top of it above 2000m asl, it also has a veneer of sub-rounded, abraded debris of mixed granitic/metamorphic provenance. Illustrated in figure 11.27 is a sub-rounded, smoothed and faceted block of hornfels (unit ***Of***), found within surficial debris at the edge of the flattened spur at GR 146686. The frequency of metamorphic blocks is significantly higher here on top of the flattened spur than the outer moraine below and adjacent to Lake Albina, which is dominantly granodiorite of unit ***ggb31***. In addition, a sub-rounded and polished quartz cobble, (figure 11.28) was also located in surficial debris on this flattened spur at 2000m asl, at GR 145687. This location is not susceptible to erosion by running water. Quartz and metamorphic rock that has weathered insitu, is revealed just north of this flattened spur and the resulting debris is invariably small and angular, not sub-rounded and smoothed.

Figure 11.27 **Sub-rounded block (200mm across) of hornfels (unit *Of*) on flattened spur at GR 146686.**
These sub-rounded, faceted and smoothed blocks, are typical of sub-glacial debris which implies that a significant ice-sheet has passed over this spur where Jennings and Galloway (1972) first noticed: "*Two granite boulders well above other granite erratics* [which] *indicate a former greater extent of Lake Albina glacier*". However, this debris had nothing to do with the small-scale cirque-style glaciation near Lake Albina that Jennings and Galloway were referring to. This debris appears to be associated with an ice-sheet moving off the Main Range.

Figure 11.28 **Sub-rounded, faceted and smoothed quartz cobble about 80mm across located on flattened spur at GR 145687 at 2000m asl.**

This sub-rounded and polished quartz cobble, was located in surficial (glacial) debris on the flattened spur at 2000m asl, at GR 145687, illustrated in figure 11.26. This location is not susceptible to erosion by running water. There are no perennial streams up on this spur which could provide the abrasion necessary to round the corners and edges of this quartz cobble. Quartz and metamorphic rock that has weathered insitu on this spur is revealed just downslope and north of the flattened spur and the resulting debris is invariably small, platy and angular, not sub-rounded and smoothed. A simple pebble like this sample (14) has an important message for those prepared to look.

The U-shaped valleys radiating outwards from Kosciuszko and the residual depositional evidence and associated geomorphic features typical of large-scale-ice abrasion, strongly suggest that an ice-field developed over the Kosciuszko Main Range prior to the late Pleistocene. The steep escarpments to the south, west and north of the Kosciuszko Plateau would have rapidly dispersed any glacial debris that passed beyond the plateau.
The apparent absence of clear-cut terminal moraines associated with this earlier phase of Kosciuszko glaciation is a product of time and topography and the surviving fragments of glacial till which have been eroded and are vegetated and overlain by modern soils, has made their identification and interpretation difficult but not impossible.
The largest fragment of glacial debris beyond any association with the cirque-like glaciation restricted to the environs of the lakes {Blue Lake, Club Lake, Albina and Cootapatamba} is represented by the terraces in the floor of the Snowy Valley below Charlotte Pass and this appears to be a recessional moraine from a valley glacier which flowed down the Snowy River valley prior to the late Pleistocene.

At the end of the day: ***If it walks like a duck, quacks like a duck, then its probably a duck.***

ENDNOTES

Endnotes Chapter One

[1] James Hutton, "Theory of the Earth," Transactions of the Royal Society of Edinburgh Vol 1: p304, 1788.

[2] Jack Repcheck, *The Man Who Found Time,* (New York: Basic Books), pp13-24, 2009. The above two paragraphs are paraphrased from this reference.

[3] James Hutton, *Theory of the Earth,* originally published 1795 and republished: (Middlesex: The Echo Library,) Vol 2(of 4), 2006.

[4] Jack Repcheck, *The Man Who Found Time,* (New York: Basic Books), pp170-179, 2009.

[5] James Hutton, Letter to George Clerk Maxwell, 1774, Scottish Records Office.

[6] James Hutton, *Theory of the Earth,* originally published 1795 and republished: (Middlesex: The Echo Library) Vol 1 Chapter v, footnote 20 and Vol 2, Chapter v, 2006.

[7] James Hutton, *Theory of the Earth,* originally published 1795 and republished: (Middlesex: The Echo Library), Vol 2, chapter vii., 2006.

[8] James D Forbes 1843. *Travels Through the Alps of Savoy and Other parts of the Pennine Chain, With Observations On The Phenomena of Glaciers*.(Edinburgh: Adam and Charles Black,1843) republished by Google Books https://play.google.com/books/reader?id=xG1CAAAAcAAJ&hl=en&pg=GBS.PT8
Accessed by E J Minty on 09 01 2019.

Endnotes Chapter Two

[9] James Hutton, *Theory of the Earth*, Volume 2, 1795. (Republished, Middlesex: The Echo Library, 2006): chapter v p58

[10] James Hutton, *Theory of the Earth*, Volume 2, 1795. (Republished, Middlesex: The Echo Library, 2006): p18

[11] James Hutton, *Theory of the Earth*, Volume 2, 1795. (Republished, Middlesex: The Echo Library, 2006): p58

[12] Horace Benedict de Saussure, *Voyages dans les Alpes,* (Neuchatel: Fauche-Borel, 1779-1796) tombe 2, p435, §1061. Note: the edition I consulted was actually published in 1803 after de Saussure's death.

[13] Louis Agassiz, *Etudes Sur Les Glaciers* (Neuchatel: Jent and Gassman,1840)1-346, note p 191.

[14] Louis Agassiz, *Etudes Sur Les Glaciers* (Neuchatel: Jent and Gassman,1840)1-346, note pp 8,9 & 13..

[15] Simon Winchester, *The Map that changed the World: A Tale of Rocks, Ruin and Redemption,* (London: Penguin Books, 2002) 1-338, note p 94

[16] Simon Winchester, *The Map that changed the World: A Tale of Rocks, Ruin and Redemption,* (London: Penguin Books, 2002) 1-338, note p 122.

[17] Simon Winchester, *The Map that changed the World: A Tale of Rocks, Ruin and Redemption,* (London: Penguin Books, 2002) 1-338, note p 202-205, & p 220.

[18] G. B. Greenough, *A Critical Examination of the First Principles of Geology: in a series of essays*. 1819 (London: Strahan and Spottiswoode) 336 pages. Note page 149

[19] G. B. Greenough, *A Critical Examination of the First Principles of Geology: in a series of essays*. 1819 (London: Strahan and Spottiswoode)336 pages. Note pps 287-292.

[20] Simon Winchester, *The Map that changed the World: A Tale of Rocks, Ruin and Redemption,* (London: Penguin Books, 2002) 1-338, note pp230-240 in relation to plagiarism.

[21] Patrick. J. Boylan,"Lyell and the dilemma of Quaternary glaciation". In Blundell, D. J. and Scott, A. C. (eds) "Lyell: the past is the key to the present", *Geological Society London, Special Publications* **143** (1998): 145-159, note pp145, 146 for material paraphrased in the above paragraph.

[22] Patrick. J. Boylan,"Lyell and the dilemma of Quaternary glaciation". In Blundell, D. J. and Scott, A. C. (eds) "Lyell: the past is the key to the present", *Geological Society London, Special Publications* **143** (1998): 145-159, note pp146-147 which discuss Agassiz and Lyell.

[23] Patrick J. Boylan, "Lyell and the dilemma of Quaternary glaciation". In Blundell, D. J. and Scott, A. C. (eds) "Lyell: the past is the key to the present", *Geological Society London, Special Publications*, **143** (1989):145-159, note p146-147 which discusses contortions in the drift at Norfolk and Lyell's terminology (***drift***), which ironically is used on British Survey maps to delineate glacial debris up to the present day.

Endnotes Chapter Three

[24] Patrick J Boylan. "Lyell and the dilemma of Quaternary glaciation," in "Lyell: the Past is the Key to the Present" eds Blundell, D.J. and Scott, A.C., *Geological Society of London, Special Publications*, **143**, (1998): 145-159, note p148 where Buckland develops plan B.

[25] Patrick J Boylan. "Lyell and the dilemma of Quaternary glaciation," in "Lyell: the past is the key to the Present" eds Blundell, D.J. and Scott, A.C., *Geological Society of London, Special Publications*, **143**, (1998): 145-159, note pp149-153 which describe the evidence for glaciation collected by Lyell in October 1840.

[26] Patrick J Boylan. "Lyell and the dilemma of Quaternary glaciation," in "Lyell: the Past is the Key to the Present" eds Blundell, D.J. and Scott, A.C., *Geological Society of London, Special Publications*, **143**, (1998): 145-159, note p153 contains a reference to a brief abstract which is all that remains of Agassiz's pioneering investigations in England, Scotland and Ireland during October 1840. The above two paragraphs were paraphrased from this reference.

[27] Patrick J Boylan. "Lyell and the dilemma of Quaternary glaciation," in "Lyell: the Past is the Key to the Present" eds Blundell, D.J. and Scott, A.C., *Geological Society of London, Special Publications*, **143**, (1998): 145-159 note the paragraph above endnote 27 was paraphrased from pp 153 & 155 .

[28] Patrick J Boylan. "Lyell and the dilemma of Quaternary glaciation," in "Lyell: the Past is the Key to the Present" eds Blundell, D.J. and Scott, A.C., *Geological Society of London, Special Publications*, **143**, (1998): 145-159 note the paragraph above endnote 28 was paraphrased from p 156.

[29] Patrick J Boylan. "Lyell and the dilemma of Quaternary glaciation," in "Lyell: the Past is the Key to the Present" eds Blundell, D.J. and Scott, A.C., *Geological Society of London, Special Publications*, **143**, (1998): 145-159, note p157 where Lyell seems to have persisted with his diluvial drift model?

Endnotes Chapter Four

[30] S. Warren Carey, 1990. *Sir Edgeworth David Memorial Oration*, Parkville: The Australian Institute of Mining and Metallurgy, P 12.

[31] David Branagan, 2005. *T W Edgeworth David A Life*, Canberra: National Library of Australia:(2005) pp 22-64. This note refers to information paraphrased in paragraphs 2-4 above relating to TWED

[32] T. W. Edgeworth David, 1895. "Evidences for Ice Action in Australia and Tasmania". Brisbane: Australasian Association for The Advancement of Science:1895 pp 1-41 plus plates is the source for the following set of Permo-Carboniferous glacial observations in Qld, NSW, Vic and Tas..

[33] Frederick Chapman,1914. *Australasian Fossils: A Students' Manual of Palaeontology*, Melbourne: George Robinson: Note pp 85-87.

[34] T. W. Edgeworth David, 1895. "Evidences for Ice Action in Australia and Tasmania". Brisbane; Australasian Association for The Advancement of Science: pp 1-41 plus plate. Note page 14.

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[35] T. W. Edgeworth David, "Evidences for Ice Action in Australia and Tasmania", *Australasian Association for the Advancement of Science*, Brisbane, (1895): 1-41, note p18.

[36] T. W. Edgeworth David, "Evidences for Ice Action in Australia and Tasmania", *Australasian Association for the Advancement of Science*, Brisbane, (1895): 1-41, note p41.

[37] T. W. Edgeworth David, "Evidences for Ice Action in Australia and Tasmania", *Australasian Association for the Advancement of Science*, Brisbane, (1895): 1-41, note p40.

[38] T. W. Edgeworth David, "Evidences for Ice Action in Australia and Tasmania", *Australasian Association for the Advancement of Science*, Brisbane, (1895): 1-41, note p35. The question marks in these quotations are amendments added by TWED.

[39] P. W. Crohn, "The Geology, Petrology and Physiography of the Omeo District, North-Eastern Victoria", *Proceedings of the Royal Society of Victoria,* v **62**, (1949) :1-70, note p12.

[40] F. C. Beavis, "Pleistocene Glaciation on the Bogong High Plains.", (A Review), *Australian Journal of Science,* v **21**, no. 6, (1959):192. Note also, that the present author has found negligible evidence of Pleistocene Glaciation on the Bogong High Plains.

Endnotes Chapter Six

[41] James Stirling, "Notes on Mt Bogong", *Reports of the Mining Surveyors and Registrars. Victorian Geological Survey, State of Victoria*,(1886): p77.

[42] Erich Blissenbach, "Geology of Alluvial Fans in SemiArid Regions", *Bulletin of the Geological Society of America*, Vol **65**: 175-190, February 1954, note pp 177-179.

[43] Edward Minty, "Late Pleistocene Geocryology of the Bogong High Plains", (Masters thesis, Sydney University, 1989): note part 1-introduction and part 2-Stratigraphy were referred to in paragraphs 2 to 8 in Ch 6 above.

[44a] John A. Talent, "Geomorphic Forms and Processes in the Highlands of Eastern Victoria" Proceedings of the Royal Society of Victoria, **78**,: 119-135, 1965. This paper is possibly the first to describe cryogenic blockstreams in Victoria.

[44b] Timothy T. Barrows, John O. Stone, L. Keith Fifield, "Exposure ages for Pleistocene periglacial deposits in Australia", *Quaternary Science Reviews*, **23**:697-708, (2004).

[44C] Edward Minty, "Late Pleistocene Geocryology of the Bogong High Plains", (Masters thesis, Sydney University,1989).note Section 2A(Description of Surficial Deposits on the Bogong High Plains) pp136-191; and Section 3: (Geomorphic Analysis of the Bogong High Plains), pp 341-411.

[45] Edward Minty, "Late Pleistocene Geocryology of the Bogong High Plains", (Masters thesis, Sydney University,1989, Section 3: Geomorphic Analysis, part D: Palaeoclimatic Inferences and Models, pp412-422.

[46] Edward Minty, "Late Pleistocene Geocryology of the Bogong High Plains", (Masters thesis, Sydney University,1989, note: Section 2: Stratigraphy/C :Correlation of 2A (Surficial deposits on the Bogong High Plains) with 2B (Surficial deposits in the upper Kiewa Valley and Mitta Mitta Valley leading up to the Bogong High Plains) pp 296-304.

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[47] S. Warren Carey, *Sir Edgeworth David Memorial Oration*, (Parkville Australia 3052: The Australian Institute of Mining and Metallurgy, 7th May 1990). Note p15.

[48] Professor David, Richard Helms, and E. F. Pitman. "Geological Notes on Kosciusko, with Special Reference to Evidences of Glacial Action." *Proceedings of the Linnean Society of New South Wales*, Part 1: 26-74, (march 27th 1901), note p 31.

[49] Professor David, Richard Helms, and E. F. Pitman. "Geological Notes on Kosciusko, with Special Reference to Evidences of Glacial Action." *Proceedings of the Linnean Society of New South Wales*, Part 1: 26-74, (march 27th 1901) Note, plates iii to x are extremely useful.

[50] J. A. Dulhunty, "On Glacial Lakes in the Kosciusko Region". *Journal and proceedings of the Royal Society of New South Wales* Vol **79**:143-152, Nov 7, 1945. Note pp 150-151. John's contoured plans of these glacial lakes is a hard won, invaluable asset.

[51] Professor David et al, 1901, p33.

[52] J. A. Dulhunty, "On Glacial Lakes in the Kosciusko Region". *Journal and proceedings of the Royal Society of New South Wales* Vol **79**:143-152, Nov 7, 1945. Note para 2, p151.

[53] Professor David et al, 1901, para 5, p33.

[54] Professor David et al, 1901, para 3, p 33.

[55] W. R. Browne, *Pleistocene Glaciation in the Commonwealth of Australia*, International Glaciological Society, Vol **3**, issue22:111-115, 1956.

[56] W. R. Browne and T. G. Vallance, *Notes on some evidences of glaciation in the Kosciusko Region*, Proceedings of the Linnean Society of New South Wales, Vol **lxxxii**, part **1**:125-144, 1957. Note their discussion of moraines on p 137.

[57] R. W. Galloway, "Glaciation in the Snowy Mountains: A Re-appraisal", *Proceedings of the Linnean Society of New South Wales*. Vol **88**/2: 180-198, (1963). Note p187, The Evidence of Landforms, part k, Moraines, para 2.

[58] R. W. Galloway, "Glaciation in the Snowy Mountains: A Re-appraisal", *Proceedings of the Linnean Society of New South Wales*. Vol **88**/2: 180-198, (1963). Note p193, discussion of "Till".

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[59] R. W. Galloway, "Glaciation in the Snowy Mountains: A Re-appraisal", *Proceedings of the Linnean Society of New South Wales*. Vol **88**/2: 180-198, (1963). Note table 1 and figure 6.

[60] Professor David, Richard Helms, and E. F. Pitman. "Geological Notes on Kosciusko, with Special Reference to Evidences of Glacial Action." *Proceedings of the Linnean Society of New South Wales*, **xxvi** Part 1: 26-74, (march 27th 1901) Note, plates iii to x are extremely useful.

[61] Professor David et al, 1901: p33.

[62] R. W. Galloway, 1963: note table 1 and figure 6.

[63] Professor David et al, 1901: p36

[64] Professor David et al, 1901: p41

[65] Professor David et al, 1901: p41

[66] Professor David et al, 1901: p 42-43

[67] Professor David et al, 1901: p47

[68] T. W. Edgeworth David, "Geological Notes on Kosciusko, with Special Reference to Evidences of Glacial Action, "*Proceedings of the Linnean Society of New South Wales*, 1908, Vol **xxxiii**, part 3, p 667.

[69] Professor David et al, 1901: p51.

[70] Timothy T. Barrows, John O. Stone, L. Keith Fifield and Richard G Cresswell, 2001, "Late Pleistocene glaciation of the Kosciuszko Massif, Snowy Mountains, Australia", *Quaternary Research* **55**, 179-189. Note p 185

[71] Barrows et al, 2001, p185.

[72] Arturo E. Corte, "Particle Sorting by Repeated Freezing and Thawing", *Biuletyn Peryglacjalny*, **15**:175-240 (1966).

[73] Edward Minty, "Kosciuszko Glaciation in the Pleistocene: Paradigm and Paradox", unpublished, 2016. Available from author tedminty49@gmail.com.

[74] Barrows et al, 2001, p183, para 3.

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[75] Edward Minty, "Late Pleistocene Geocryology of the Bogong High Plains", (MSc thesis submitted to Department of Geology and Geophysics, University of Sydney), May 1989

[76] Arturo E. Corte, "Particle Sorting by Repeated Freezing and Thawing", *Biuletyn Peryglacjalny*, **15**:175-240 (1966). Note pp220-237.

[77] Havard Juliussen and Ole Humlum, "Thermal Regime of Openwork block Fields on the Mountains Elgahogna and Solen, Central-eastern Norway", *Permafrost and Periglacial Processes*, **19**:1-18, (2008)

[78] A. Rist, M. Phillips and S. M. Springman, "Inclinable Shear Box Simulations of Deepening Active Layers on Perennially Frozen Scree Slopes"*, Permafrost and Periglacial Processes,* **23**:26-38 (2012).

[79] Arturo E. Corte, (1966) note part VI, pp220-222 and figure 31.

[80] N. Caine and J. N., Jennings, "Blockstreams of the Toolong Range Kosciusko State Park, New South Wales", *Proceedings, Royal Society of New South Wales*, Vol **104**:93-103 (1968). Note p96, description of excavation into blockstream 1.

[81] N. Caine "The Blockfields of Northeastern Tasmania", Research School of Pacific Studies, Department of Geography Publication G/6, 1968. Note p39 and p101 for reference to vertical sorting.

[82] Edward Minty, 2021 , "Cryogenic Block Deposits at Basalt Hill", published online at Academia.edu

[83]Hales, T. C., and J. J. Roering, 2007. "Climatic controls on frost cracking and implications for the evolution of bedrock landscapes". Journal of Geophysical Research., **112**:1-14

[84] Washburn, A. L., *Geocryology A survey of periglacial processes and environments*. (London: Edward Arnold 1979),note pp 237-243 and figures 7.2, 7.3 & 7.5.

[85] Edward Minty, May 1989. Note the stratigraphy of surficial debris at Basalt Hill in pp42-107; and also the geomorphic analysis of Basalt Hill in pp 341-364.

[86] Edward Minty, May 1989. Note especially the descriptions of block weathering at sites 10, 11 and 14 in endnote 8 above: Stratigraphy of surficial debris at Basalt Hill. pp 42-107.

[87] N. Caine and J. N., Jennings, "Blockstreams of the Toolong Range Kosciusko State Park, New South Wales", *Proceedings, Royal Society of New South Wales*, Vol **104**:93-103 (1968). Note p96, description of excavation into blockstream 1.

[88] Edward Minty, unpublished fieldnotes: 26/3/2017-20/01/2019 measurements of upper and lower weathering rinds of basalt blocks at Station blockstream (Ravine, KNP); block glacis at Mt Little Higginbotham; block glacis at Basalt Hill, Bogong National Park; all have a similar range and pattern in depth of weathering rinds.

[89] Edward Minty, May 1989. Note pp192-304.

[90] Erich Blissenbach, "Geology of Alluvial Fans in Semiarid Regions", Bulletin of the Geological Society of America, **66**:176-190, Feb 1954

[91] Stuart A. Harris "Climatic Zonality of Periglacial Landforms in Mountain Areas", *ARCTIC* **47**(2):184-192. Note figure 13 and table 1.

[92] Wilfried Haeberli, "Modern Research Perspectives Relating to Permafrost Creep and Rock Glaciers: a Discussion", *Permafrost and Periglacial Processes*,**11**: 290-293 (2000).

[93] A. Ikeda & N. Matsuoka and A. Kaab. "A rapidly moving small rock glacier at the lower limit of the mountain permafrost belt in the Swiss Alps" in *Permafrost* (eds) Phillips, Springman & Arenson (Lisse: Swets & Zeitlinger, 2003), 455-460.

[94] Christophe Lambiel and Reynald Delaloye. "Contribution of Real-time Kinematic GPS in the Study of Creeping Mountain Permafrost: Examples from the Western Swiss Alps," *Permafrost and Periglacial Processes* **15** (2004):229-241.

[95] Timothy T. Barrows, John O. Stone, L. Kieth Fifield and Richard G Cresswell, 2001, "Late Pleistocene glaciation of the Kosciuszko Massif, Snowy Mountains, Australia", *Quaternary Research* **55**, 179-189. Note para 3, p185.

[96] Timothy T. Barrows et al, 2001, note Table 1, p184 and para 3, p 185.

[97] Timothy T. Barrows et al, 2001, note Fig 5, p 187.

[98] Timothy T. Barrows et al, 2001,note table 1 p 184 and para 3 p185.

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[99] Timothy T. Barrows, John O. Stone, L. Keith Fifield and Richard G Cresswell, "Late Pleistocene glaciation of the Kosciuszko Massif, Snowy Mountains, Australia", *Quaternary Research* **55**, (2001), p 184 (table 1)

[100] Timothy T. Barrows, John O. Stone, L. Kieth Fifield and Richard G Cresswell, "The Timing of the Last Glacial Maximum in Australia", *Quaternary Science Reviews* **21**, (2002), pp168-169.

[101] Barrows et al, (2001) pp186-188

[102] Barrows et al, (2001) p187.

[103] Timothy T. Barrows, John O. Stone, L. Kieth Fifield, "Exposure ages for Pleistocene periglacial deposits in Australia", *Quaternary Science Reviews* **23**, (2004), p704 table3.

[104] Barrows et al, (2004), p704 table3.

[105] Sandra McLaren and Malcolm W Wallace, "Plio-Pleistocene climate change and the onset of aridity in southeastern Australia". *Global and planetary Change*, **71**, (2010), p57-65.

[106] McLaren and Wallace, (2010) p66

[107] McLaren and Wallace, (2010) p66

[108] McLaren and Wallace, (2010) p66-67 note figure 11.

[109] Eric A. Colhoun, Kevin Kiernan, Tim Barrows & Albert Goede, "Advances in Quaternary studies in Tasmania." From Bishop, P. & Pillans, B. (eds) Australian Landscapes. *Geological Society, London*, Special Publications, **346** (2010)165-183

[110] Colhoun et al, (2010), p165.

[111] Colhoun et al, (2010), p170.

[112] J. L. Davies, *Landforms of Cold Climates*, (Canberra: Australian National University Press, 1972) ,p 17, and figure 3, pp4-5.

[113] Colhoun et al, (2010), p172.

[114] Barrows et al, (2001), p180.

[115] Edward Minty, "Kosciuszko Glaciation in the Pleistocene: Paradigm and Paradox", unpublished, 2016. Available from author tedminty49@gmail.com., p20 and figure 8.

[116] Karen E. Kohfeld and Sandy P. Harrison, "DIRTMAP: the geological record of dust". *Earth Science Reviews,* **54**:81-114 (2001)

[117] Kohfeld and Harrison,(2001) figure1,p82.

[118] Kohfeld and Harrison,(2001), p102.

[119] Kohfeld and Harrison,(2001), p102.

[120] J. Lomax, A. Hilgers and U. Radtke, "Palaeoenvironmental change recorded in the Palaeodunefields of the western Murray Basin, South Australia- New data from single grain OSL-dating". *Quaternary Science Reviews***, 30**:723-736 (2011), note p734

[121] Lomax et al, (2010), p724.

[122] Washburn, A. L., *Geocryology A survey of periglacial processes and environments*. (London: Edward Arnold 1979), p222.

[123] Stuart A. Harris, "Climatic Zonality of Periglacial Landforms in Mountain Areas". *ARCTIC* **47**(2):184-192 (1994).

[124] Stuart A. Harris, 1994, p188

[125] Stuart A. Harris, 1994, p189

[126] Stuart A. Harris, 1994 p185

[127] Stuart A. Harris, 1994, note figure 13 p188.

[128] M. W. Smith and D. W. Riseborough, "Climate and the Limits of Permafrost: A Zonal Analysis". *Permafrost and Periglacial Processes***, 13**:1-15 (2002)

[129] Bernd Etzelmuller, Herman Farbrot, Agust Gudmundsson, Ole Humlum, Ole Einar Tveito and Helgi Bjornsson, "The Regional Distribution of Mountain permafrost in Iceland". *Permafrost and Periglacial processes*, **18**: 185-199 (2007)

[130] K. Priesnitz and E. Schunke, "The Significance of Periglacial phenomena in Iceland", *Polarforschung*, **53**:9-19 (1983)

[131] Agust Gudmundsson, personal communication, July 2011. Contact: GEOICE Geological Services; jardis@geoice.net

[132] Edward Minty, "Late Pleistocene Geocryology of the Bogong High Plains", *University of Sydney* thesis submitted May 1989 (unpublished).note pp 382-411.

[133] NSW Government, Office of Environment and Heritage, 2012 "Peat-forming bogs and fens of the Snowy Mountains of NSW", Geoffrey Hope, Rachel Nanson and Peter Jones, April 2012 note pp51-55

[134] Arturo E. Corte, "Particle Sorting By Repeated Freezing And Thawing", *Biuletyn Peryglacjalny*, **15**:175-240 (1966); note Part VI pp220-222.

[135] Minty, 1989, p393.

[136] R. W. Galloway, "Glaciation in the Snowy Mountains: a re-appraisal", Proc Linnean Society of New South Wales **88**/2:180-198. Note description of exposure near Island Bend on p194.
Endnotes Chapter 11

Endnotes Chapter Eleven

[137] T. W. Edgeworth David, "Geological Notes On Kosciusko, With Special Reference To Evidences Of Glacial Action Part II", *Proc of the Linnean Society of New South Wales*, Vol xxxiii, part 3:657-668 (1908). Note page 667 for David's summary

[138] T. W. Edgeworth David, 1908. p662

[139] R. W. Galloway, "Glaciation in the Snowy Mountains: A Re-appraisal", *Proceedings of the Linnean Society of New South Wales*. Vol 88/2: 180-198, (1963). Note the synopsis for a summary of Galloway's model. Galloway's figure 6 has been reproduced by the Bureau of Mineral Resources in the1990 Glacial Inset Map as part of the Geology of Kosciusko Map.

[140] Timothy T. Barrows, John O. Stone, L. Kieth Fifield and Richard G. Cresswell, "Late Pleistocene glaciation of the Kosciuszko Massif, Snowy Mountains, Australia", *Quaternary Research* **55**, (2001), note table 1 and p183, para 3.

[141] R. W. Galloway, 1963, p 181, para 2.

[142] R. W. Galloway, 1963. Pages 192-193 contain several fictional arguments based on flimsy generalisations and lacking analysis of any specific pieces of evidence. For example it would be absurd to postulate that the morphology and surface texture of the block illustrated in figures 11.3 and 11.4 were caused by slickensides on a single joint plane, given that each of seven different facets on this block were striated. Secondly, slickensides is usually a fine paste-like layer resulting from movement between two adjoining joint blocks and is quite fragile when exposed, whereas striations have been cut into a hard polished facet of quartzite in the above figures. I query whether Galloway has ever seen an example of slickensides anywhere in the field let alone on the Kosciuszko Plateau. The other argument that random outcrops of metamorphic rock occur throughout the granitic terrain is also a fiction

and not one of these belts of metasediments including those actually mapped by the BMR in 1990 occur anywhere near Spencers Creek.

[143] Douglas I. Benn and David J. A. Evans, *Glaciers and Glaciation, 2nd edition*, London, Hodder Education:1-802, 2010, Note pp 356-362 clast morphology and Chapter 8.2: sub-glacial erosion.

[144] R. W. Galloway, 1963, p 191, "The evidence of Erratics". Galloways list of prior records of erratics appears incomplete and summarily dismisses reports of quartzite erratics which are prime suspects because they are easy to differentiate from xenoliths and they are the best rock type in terms of recording glacial abrasion and preserving it as polished and striated surfaces.

[145] T. W. Edgeworth David, 1908, p164.

[146] T. W. Edgeworth David, 1908, p662.

[147] T. W. Edgeworth David, 1908, p664.

[148] W. R. Browne and T. G. Vallance, "Notes On Some Evidences Of Glaciation In the Kosciusko Region", *proceedings of the Linnean Society of New South Wales*, Vol lxxxii, part 1: (1957). Note p138 "*Striated stones of quartzite have been picked up on the eastern flank of Guthrie Range at 6,165 feet, more than 400 feet above the floor of Spencers valley*"

W. R. Browne and T. G. Vallance, "Further Notes On Glaciation In the Kosciusko Region", *proceedings of the Linnean Society of New South Wales*, Vol lxxxviii, part 2:112-129, (1963) Browne and Vallance discuss the metasedimentary erratics in the catchment of Spencers Creek valley in paragraph 3 of page 117.

[149] Professor David, Richard Helms, and E. F. Pitman. "Geological Notes On Kosciusko, With Special Reference To Evidences Of Glacial Action." *Proceedings of the Linnean Society of New South Wales*, Part 1: 26-74,(march 27th 1901). Reference to "Tumbled quartzite blocks" located on the interfluve NE of the Etheridge Range is noted on plate (iii).

[150] R. W. Galloway and J. N. Jennings, "Notes on Cold Climate Geomorphology in the Snowy Mountains of New South Wales", Tenth Conference Institute of Australian Geographers, Canberra:6th Feb, 1972: 1-7 and an Addendum by J.N. Jennings:4th Nov 1976. Note figure 1 and in particular the distribution of metasediments. The bulge occurs on the interfluve at the northern extension of the Etheridge Range and suggests that the authors of this figure failed to check the strike of the metasediment belt in this region. Worse still, they may have assumed that the slabs of metasediment sitting on their broad sides, were insitu in contrast to T. W. E, David's 1901 note on his plate (iii).

[151] R. W. Galloway, 1963, p193, para 2.

[152] Douglas I. Benn and David J. A. Evans, *Glaciers and Glaciation, 2nd edition*, London, Hodder Education:1-802, 2010. Note pp 356-362 clast morphology and Chapter 8.2: sub-glacial erosion.

[153] Douglas I. Benn and David J. A. Evans, *Glaciers and Glaciation, 2nd edition*, London, Hodder Education:1-802, 2010. Benn and Evans put forward arguments that roches moutonnées are erosional forms encouraged below thin, temperate valley glaciers and/or they are immature glacial erosional forms that would be completely removed by lee-side cliff retreat under prolonged glaciation. Refer to pp277-280.

[154] Professor David et al, 1901. The ice scratched blocks south of Rawson Pass are described on pp 33 and 34.

[155] Professor David et al, 1901. Blocks of phyllite and quartzite on the eastern flank of the moraine, p34.

[156] Professor David et al, 1901. Investigation downstream of Lake Cootapatamba, p35.

END